after Francis Buchanan, a Surgeon to the Governor General of India, whose mastery work in 1807 on the survey of south India resulted in his monumental work *"A Journey from Madras through the Countries of Mysore, Canara and Malabar"*. Buchanan noticed, during his journey across South India, metal craftsmen producing crucible steel using a particular furnace which he documented and this furnace is now known after his name and classified as the Buchanan Furnace. The model of the Buchanan Furnace in the exhibit is duly supplemented with research findings on the uniqueness of the Wootz ingots and how this Wootz steel was used for producing the world famous Damascus swords. The method used by ancient Indians for producing Wootz steel ingots has also been duly presented[35].

The process of Wootz crucible steel making was very much associated with the South Indian part of the subcontinent including Sri Lanka[36]. The strange word Wootz was coined when European travellers from the 17th century onwards came across the making of steel by crucible processes in Southern India in the states of Tamil Nadu, Andhra Pradesh and Karnataka. Wootz is an anglicized and corrupted word for the local Kannada and Telugu word *ukku* meaning steel. The megalithic site of Kodumanal, 300 BC, in Tamil Nadu was one of the ancient sites for ferrous crucible processing. This date also supports an early literary reference to steel from India and Mediterranean sources including the one from the time of Alexander (300 BC) who was said to have been presented with 100 talents (a Greek measurement/unit for mass equivalent to 26 Kgs) of Indian steel[37]. There is also a preliminary identification of a sample of high carbon steel of the composition of Wootz of around 1.5% carbon from megalithic Andhra Pradesh. These are tentatively the earliest known identifications for high-carbon crucible steel any where in the world.

Bronze Statues

Medieval South Indian Bronze Idols, also known as *panchaloha idols*[38], especially the idols of various deities including *Natraj*, are internationally acclaimed for their elegance, aesthetic beauty, iconographic details and distinctive metal craftsmanship. These idols not only portray technological excellence but also represent aesthetic qualities of forms that are exquisite and unique only to South Indian bronze icons[39]. Many of these treasured bronze idols can be found in temples across South India and also in different museums in India and abroad specially the Government Museum in Chennai. These bronze icons have been recognized for their unique identity. In the year 2007 and on the eve of the 60th year of India's independence, a special exhibition of the Chola Bronzes was organised at Royal Academy of Arts in London. This exhibition, "Chola: Sacred Bronzes from Southern India" enticed one into the intricate world of Chola bronzes (ninth to thirteenth centuries AD) that fluidly captured in bronze the sensuous visions of Tamil poet-saints. These icons epitomized aspects which lie beyond the artifact and its visual appearance.

It is in recognition of this unique ancient metal tradition, which is continuing to be practiced even today, that we have included one exhibit to cover this metal crafts technology. The exhibit has on display a sequence of the objects that form different stages in the making of the South Indian Bronze idols/icons and also the raw materials that are used in the making of these icons. The display is well supplemented with information and a specially made video which depicts the process involved in making bronze statues in traditional style, the period of which goes back to more than 2000 years.

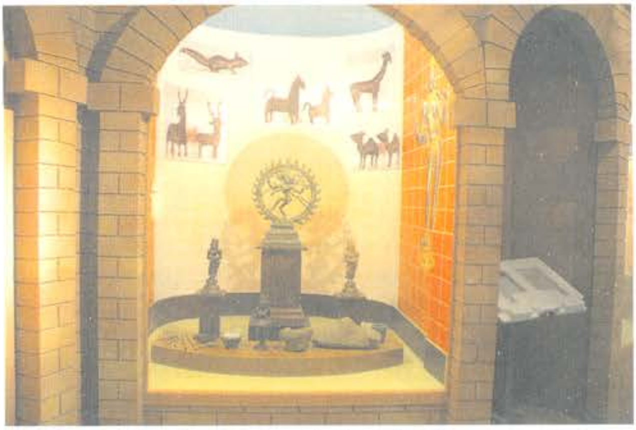
Fig. 8. The Chola Bronze exhibit (with the statue of Natraj) supported by a film which shows the process involved in making Chola bronze statues.

The specialty of the bronze icons can best be understood in the words of R Nagaswamy[40], a notedSouth Indian historian and an expert on South Indian bronzes, who says *"The bronzes were part of sacred architecture, the living legacy of an unknown master artist who rendered these subtle and fluid forms as a means of expressing the divine. Made in accordance with codified principles, and sanctified by worship, these images were the link between Man and his God"*. This traditional metal crafts of South Indian bronzes is believed to be in practice since at least 2000 years. The metal craft centres in Kanchipuram, Kumbakonam and Madurai in Tamilnadu, which produce these stunning statues, have shown a remarkable continuity of this traditional crafts. The first archeological material evidence for the bronze castings in India however go back to the period of Harappans during which the famous *Dancing Girl* statue cast in bronze was found in Mohenjodaro which is 4500 years old. The 10.8 cm long bronze statue of the dancing girl was found in 1926 from a house in Mohenjodaro and this object is presently preserved in the National Museum at Delhi. The material evidence of the bronze statue from South India is seen from the bronze objects (presently preserved in the Government Museum, Chennai) obtained from the excavations at Adichanallur in Tirunelveli district of Tamilnadu. The continuing tradition of bronze statue in South India begins from the Pallava period (3rd to 9th century AD), this craft however reached its zenith during the Chola period (9th to 13th century AD), during which very high quality bronze icons of deities were made in large numbers. This tradition was further encouraged by the Vijayanagara kings during the 15th and 16th century[41].

Bronze statues of South India were mostly made using the solid casting or Lost Wax method (cire-purdue process) as per the process mentioned in the texts of *Shilpa Shastra* which presents the steps involved in the making of bronze statues in original sanskrit form[42,43].

Zinc Smelting

India's primacy in brass and zinc metallurgy is now well established and the archeological evidence suggests that Indians were the first to begin zinc smelting using the distillation process some times during 5th-4th century BC[44]. Indians were also the first to produce industrial level production of Zinc at the Zawar mines in Rajasthan between 13th and 18th century long before the much credited Industrial Revolution in Europe. Zinc smelting in Europe began only in 1730 when William Champion, of the champion process fame, began production of zinc using a process which bear striking similarity to the one used in the Zawar mines[45]. This point of view that Champion may have learnt of the process of zinc smelting from the works of the ancient Indians is further substantiated by Paul Craddock who says *"Champion was notoriously close with details to Indian process at Zawar; possibly a third party described the general principles of the process to Champion"*[46].

A staggering 100,000 tonnes[47] of zinc was produced at the Zawar mines from 13th to 18th century. The smelting of zinc in such large scale of production was one of the most challenging technologies of the pre-modern world in which modern industrial practices had to be adopted using applications of scientific techniques for producing hundreds of thousands of tones of zinc[48].

Extraction of zinc is difficult unlike other metals. Normally, metals like lead, copper, tin, etc are smelted in a simple furnace and collected as molten mass at the bottom. Zinc cannot be smelted in simple furnaces since at high temperature conditions, zinc, with its low boiling point (907°C), vaporizes and re-oxidizes and gets lost in air. Therefore, zinc extraction requires a different process for smelting the ore and for retaining the vapour and condensing the same. As early as the 12th century AD, India produced the metallic zinc by the sophisticated distillation process at Zawar in Rajasthan. Zawar, 45 kms south of Udaipur city, was the major producer of zinc and an advanced zinc mining and smelting activity flourished in this area during the 13th to 18th century AD. It is therefore no wonder that even today Rajasthan is the principal producer of zinc in India and one of the leading companies of zinc production in India, the Hindustan Zinc Ltd, started its commercial mines operation from Zawar mines in the year 1983. Extraction of zinc metal from its ores had posed problems during the earliest times in other countries in the world and metallic zinc was rarely reported in antiquity. The technique of reverse distillation process used in ancient India for smelting of zinc and its manufacture is also described in several early Indian alchemical works of the mediaeval period including the 13th century *Rasa Ratna Samuccaya*. The word used in this document to describe the distillation process involved is *tirakpatnayantra*, which translated literally, means "distillation by descending". This ancient Indian text has a detailed description of the process of high temperature distillation that was developed and applied in this country for extraction and purification of the zinc metal from the ores. There are also other earlier ancient texts, Rasarnavam Rasatantram (500 BC) and Rasaratnakara (2 century AD), which contain descriptions on zinc[49].

Zinc distillation furnace at Zawar: a model reproduced at the gallery

In recognition of the magnificent and unparalleled contribution of ancient India in zinc smelting, an exhibit consisting of a model (replica) of the ancient zinc smelting furnace from the Zawar mines has been developed and showcased in the gallery. This exhibit

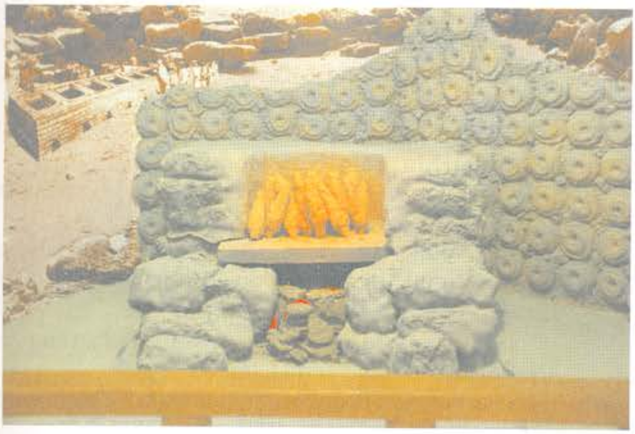

Fig. 9. Zinc smelting exhibit with the reconstructed model of *Koshti* ancient Indian Zinc furnace.

is adequately supplemented with visually rich information and some original retorts from the excavation sites of Zawar mines. The model reproduced in the gallery is based on the archaeological excavation carried out by Hindustan Zinc Ltd, British Museum and University of Baroda which has unearthed intact ancient zinc distillation furnaces at Zawar with banks of between three and seven furnaces each of which held 36 retorts. The photographic remains of excavations at Zawar are also shown in the exhibit. These furnaces were used to carry out one of the most sophisticated pyrometallurgical operations for extraction of zinc. The distillation furnace, a model of which is shown in the exhibit, is divided into two parts. A lower condensing chamber separated by a perforated plate and the main furnace chamber. Retorts containing the zinc ores are also displayed in the model. The furnace has small holes alternately and this served the purpose of passage of air into furnace and for the burnt ash to drop through. The whole area in front of the furnace was paved with large bricks. Each of the furnaces shown in the exhibit could produce between 20 and 25 kg of zinc metal per day.

The Retorts (originals from the excavation sites of Zawar) displayed in the exhibit consist of a cylindrical portion and a tapering portion at one end and these retorts resemble the shape of a Brinjol. A zinc ore separated by hand picking was roasted in air, to convert to zinc oxide. Roasted mass together with reducing agents and fluxes such as charcoal, dolomite, salts etc were ground and made into small balls using organic material as binder and were filled in the cylindrical portion. This was done not only to stop the charge from falling out of the retort when it was initially inverted in the furnace, but also to facilitate escape of zinc vapour formed during firing. The exhibit also has a visual showing the patent drawing of William Champion, from which the visitor can form an intellectual hypothesis that Champion was perhaps influenced by the techniques of ancient Indians used in Zawar mines.

(to be concluded in Part III)

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Incorporating Visitor Experience into Exhibition Design Deconstructing a Student Project

Gretchen Jennings and **Karen Lee**

Abstract

The Raja at length, being desirous of seeing with his own eyes how his Education Department busied itself with the little bird, made his appearance one day at the great Hall of Learning. From the gate rose the sounds of conch-shells and gongs, horns, bugles and trumpets, cymbals.... The pundits began chanting mantras with their topmost voices, while the goldsmiths, scribes, supervisors...loudly raised a round of cheers.... The Raja said: "it does seem so fearfully like a sound principle of Education!" The Raja was about to remount his elephant, when the fault-finder, from behind some bush, cried out "Maharaja, have you seen the bird?" "Indeed I have not!" exclaimed the Raja, "I completely forgot about the bird."

The Parrot's Training *by Rabindranath Tagore*[1]

Rabindranath Tagore's parable about the education of the parrot can be seen as a reminder to museum professionals everywhere. How many times do we forget the visitor? How often do we build elaborate museums and expensive displays without ever talking to visitors in order to understand what will serve them best? This article examines a project created by the authors and conducted with their students during the nine-day "Science Learning in Non Formal Settings" course for the MS in Science Communication in Kolkata in November 2009. The purpose of the project was to provide the students with a brief but intense experience in how to incorporate visitor voices and understandings into the conceptualization and design (or re-design) of exhibitions. In addition to describing the project itself, the authors will also discuss its theoretical underpinnings. The experience itself took place in the last four days of the course. The previous five days of class involved reading and discussion of research in science education, learning theory, developmental and cognitive psychology, design of informal spaces, visitor research, visitor evaluation processes, and other studies of museum practice. The article concludes with the authors' assessment of the students' experience and of the successes and challenges of the project.

Incorporating the visitor voice. It is a subject that is explored with increasing frequency in books[2], conferences[3], journals[4], and websites[5]. Why should museums include this perspective in their planning and development of exhibitions and programs? In what forms? By what means?

In November 2009 the authors were members of a group of Smithsonian-sponsored faculty teaching in the MS in Science Communication program at the main campus of the National Council of Science Museums (NCSM) in Kolkata, India. Our ten students consisted of six museum professionals with years of experience as curators, designers, or educators, and four Fellows at the beginning of their museum careers. We decided to expand our course—normally focused only on non-formal learning---to include the study of family learning in museums and methods of incorporating visitor feedback into the interpretive planning process. A key goal in our joint effort was to address this issue of the visitor voice and its role in exhibition development, which research links to improved visitor engagement and understanding[6]. How could we emphasize the importance of this concept in the students' formation as science museum communicators?

We proposed combining traditional classroom teaching and discussion with a workshop in which students would have to redesign an exhibit based on visitor feedback. In keeping with the theories we were teaching about active and experiential learning, we concluded that the best way to teach about incorporating the visitor voice would be to model some best practices that have been developed over years of study and research in museums. We would create a brief but intense experience in soliciting, listening to, and integrating visitor voices and understandings into the conceptualization and design (or re-design) of an exhibition. We hoped to provide students with new skills and the confidence to utilize them back at their museums.

Description of the Student Project

Background

On one of our first days in Kolkata, before the course had begun, the authors visited Science City, a large, popular science museum and science park. We were looking for an exhibition component that did not seem to engage visitors as the curators had no doubt intended. We spent several hours observing, talking with visitors, and photographing exhibits both with and without visitors. After discussing our afternoon's work and reviewing our notes and photographs, we decided that a component called "Principles of Flight", featuring sections on both "lift" and "drag", might be a candidate for our student project.

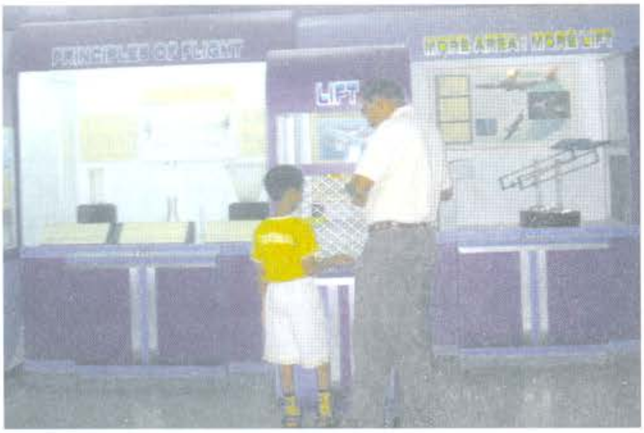


Fig. 1. "Principles of Flight" exhibit at Science City, Kolkata, India.

The component, shaped like a large squared-off "U", contained artifacts and a discussion of the physics of flight in the middle section. Each of the two "arms" of the U had a button-activated interactive element and explanatory text, one side on "lift" and the other on "drag", two aerodynamic forces that must be understood in order to learn how airplanes fly. Visitor groups stopped briefly at each section; some operated the interactive; few read the text. Family groups in particular did not spend much time reading or operating the interactive parts. A few visitors, with whom we could speak in English, told us that they understood the text because they already knew what "lift" and "drag" meant, but they did not think the ordinary visitor would grasp the technical explanations.

Using Borun's Family Learning Study as Our Model

Following our visit to Science City, we began our class with reading, analysis, and discussion of current findings and best practice in learning theory and visitor studies. We will discuss this theoretical material later in the article, applying it to the prototype the students created. As our work shifted in preparation for making revisions to the "Lift" & "Drag" exhibits, we focused on an important piece of research on family learning in museums. The study, led by researcher Minda Borun, involved four science learning spaces in the city of Philadelphia, Pennsylvania, USA. Each facility (the Academy of Natural Sciences, The Franklin Institute, the Philadelphia Zoo, and the New Jersey State Aquarium) had selected a component that it hoped to improve for use by families or other multigenerational groups. After observing and talking with visitors using each component, the Borun research team developed an observation form that focused on behaviors that appeared to be linked to engagement and retention of information about the components – reading, pointing, talking with each other, engaging with the activities, etc. They also developed interview questions designed to assess a family's level of engagement with an understanding of the key ideas of the exhibit. The research teams then used observation, interviews, and videotaping of family groups at each of the components to discover what elements might encourage more engagement and learning. They modified each element incrementally, observing and interviewing each time, until the exhibit held families' attention, engaged them in the activity and in conversation with each other, resulting in increased understanding of the exhibit's goals. Based on this study, which was conducted during three phases with over 500 families at the four locations, Borun and colleagues developed seven principles of family-friendly exhibits:

1. Multi-sided: the family can cluster around the exhibit.
2. Multi-user: interaction allows for several sets of hands and bodies.
3. Accessible: the exhibit can be comfortably used by children and adults.
4. Multi-outcome: observation and interaction are sufficiently complex to foster group discussion.
5. Multi-modal: the activity appeals to different learning styles and levels of knowledge.
6. Readable: the text is arranged in easily-understood segments.
7. Relevant: the exhibit provides cognitive links to visitors' existing knowledge and experience[7].

Our student project aimed at reproducing this study in miniature, requiring students to combine learning theory with the practice of visitor-centered design. Most of our students were familiar with the "Lift" & "Drag" exhibits as they had been presented in science centers for many years, so these components were an interesting choice for re-design.

Phase 1: Designing the Observation and Interview Sheets

Before we could embark on an interpretive redesign of the exhibit components, we needed to understand how visitors were using the current ones. During class discussions, the students became acquainted with a large body of scholarship on how to collect, interpret and utilize visitor behavior data[8] as part of the exhibition planning process. When it was time to put that information to work, the instructors were pleased that many students were eager to apply the academic precepts to actual visitors.

Yet some students seemed less convinced, asking exactly how a small, informal sample of visitor data could lead to substantive insights or an "improved" exhibit. As with many museum professionals, there is a tendency to think that visitor assessments must always be based upon hundreds of observations, expensive prototypes, complex statistical analysis, and lengthy reports. While large-scale studies are sometimes necessary, in this instance we opted to use a method that would fit the time constraints and resources of our class project. We decided to develop an observation sheet much like the one used in the Borun study. The student observers, using one form per family, would watch to see if families engaged with the exhibit, read the text, asked or answered questions among themselves.

The students did not anticipate the challenge of writing effective interview questions. Before they had actually experienced visitor observation and testing, the students had conflicting ideas about the vocabulary to use in the survey, the learning outcomes to look for, and even the number of questions to ask. Later they would realize that watching and talking with visitors brought clarity to the process of developing good questionnaires. More immediately obvious was the need for translation. The students wrote the questionnaires in English, and then created written translations in Hindi and Bengali. Of course all of the students spoke both English and Hindi, and about half also spoke Bengali.

Two questionnaires were created, one for the "Lift" exhibit and one for the "Drag" exhibit. Research in the United States indicates[9] that using phrases like "in your own words" alleviates some of the self-consciousness people may feel if they sense they are being judged for their answer, so the exact phrasing of each question became a careful construction. Each survey began with "in your own words, explain what "lift" ("drag") is". Each contained four questions (see Appendix A) that investigated how the exhibits were used and understood. We had to assume that this wording would work well with Indian audiences. It might be an interesting future project to study what kinds of interview wording work best in different languages and cultures. We created two teams of five students each, a "lift" team and a "drag" team. Each team consisted of three museum professionals and two Fellows.

Phase 2: Observation and Discussion with Visitors

On Saturday morning, a day when many families visit Science City, we met our students at the museum. We planned that members of each team would take on

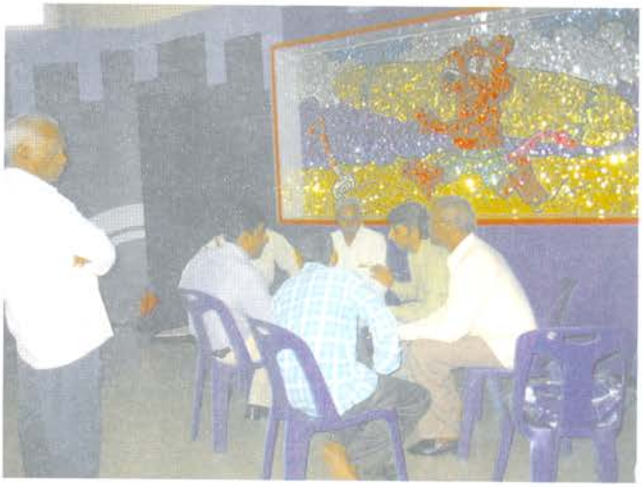


Fig. 2. NCSM student (center) interviewing a visitor group at Science City.

explained the project and asked if visitors would be willing to be interviewed after they had looked at the exhibit; if families were not approaching on their own, a recruiter would seek out people, explain the project, and bring willing groups over to the exhibit; **observers** stood unobtrusively near the "lift" and "drag" sections of the exhibit, and completed an observation form for each family; and **interviewers** (at least one of whom spoke Bengali) talked with families after they had tried either the "lift" or "drag" section of the exhibit.

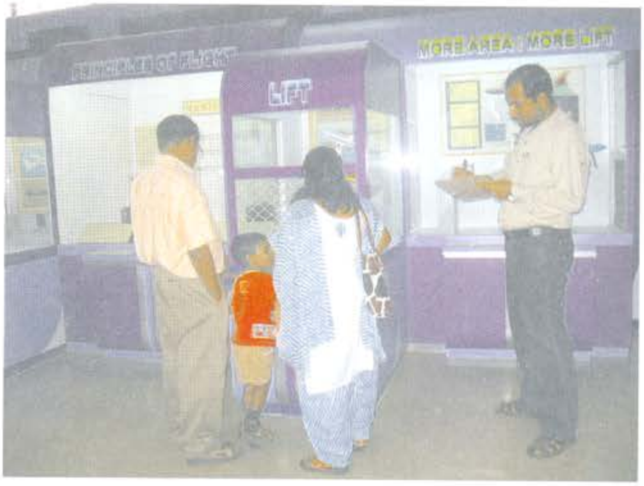


Fig. 3. NCSM student observing a family at the "Lift" exhibit.

Observers and interviewers also had to work together to link the observations and interview notes for the same family. We had hoped that all students could rotate through the three roles throughout the morning, but we were able to organize only two rotations. The first half hour or so was a bit disorganized, with the students learning their roles "on the job", and we two instructors trying to be everywhere at once, answering student questions, coaching students' interactions with visitors, and documenting the project with our cameras. But the study soon settled into a smooth pace, with recruiters, observers, and interviewers working together with the family groups.

Phase 3: Decoding Visitor Understanding of "Lift" & "Drag"

At the end of the morning we retired to a nearby classroom, and debriefed with a welcome offering of tea and cookies from the museum. The students first discussed their findings within their own groups, and we then talked as a whole class. The immediate conclusion of both groups was that the visitors had understood almost nothing about "lift" and "drag". Upon further examination of the visitors' own words, however, we came to see that they did have their own understandings of these concepts, based on their personal prior knowledge and what they experienced in doing the interactive. But what visitors understood about how to operate the exhibits and the concepts they presented was always not what the museum intended. The students discovered that visitors were confused by how to operate and understand the exhibits. As they had learned in class, this was not a problem unique to Science City[10].

Technical understanding: Visitors did not understand that they had to hold the button to keep air flowing from a blower that would activate the exhibit. They pressed the button and walked away.

Vocabulary issues: Overall most family groups did not understand the exhibit and rarely read the labels, which had terms (*aerofoil, aerodynamic, fuselage*), that were difficult to understand. A number of visitors asked why the text was not in Bengali as well as Hindi and English.

Prior knowledge shaped/interfered with understanding: Most visitors had never flown so were unable to relate the concept of "lift" or "drag" from personal experience of a plane. People seemed to think the exhibit was about plane wings tilting rather than actually flying. People who had flown thought it might have something to do with turbulence.

Cultural issues: Women in mixed-gender groups rarely activated the exhibit. Mainly they watched while the men engaged with the activity though they would engage in discussion about exhibit topics despite their lack of participation. Women alone with children did engage with the exhibit.

Phase 4: Redesigning "Lift" and "Drag" to Optimize Visitor Experience

Our challenge to the students (and to ourselves): Could we redesign the "lift" and "drag" exhibits, including the text and graphics, taking into consideration visitors' perceptions and misperceptions in a way that would improve their understanding of these two principles of flight?

We spent the next two days of class reflecting on what the students had observed at the "Principles of Flight" exhibit. We approached the prototyping process with a blend of the theoretical and the practical: reviewed what the visitors had said about their understanding of the exhibit and text; associated our observations with research about why the human brain resists releasing inaccurate concepts about scientific phenomena for accurate ones[11]; and brainstormed the kinds of experiences that might engage visitors and connect to their everyday understandings of "lift" and "drag". Finally, we developed prototypes out of Styrofoam, lightweight wood, and construction paper, using materials such as tape, glue, scissors, and markers, provided by the NCSM program; tested the prototypes with each other; wrote text; and created graphics.

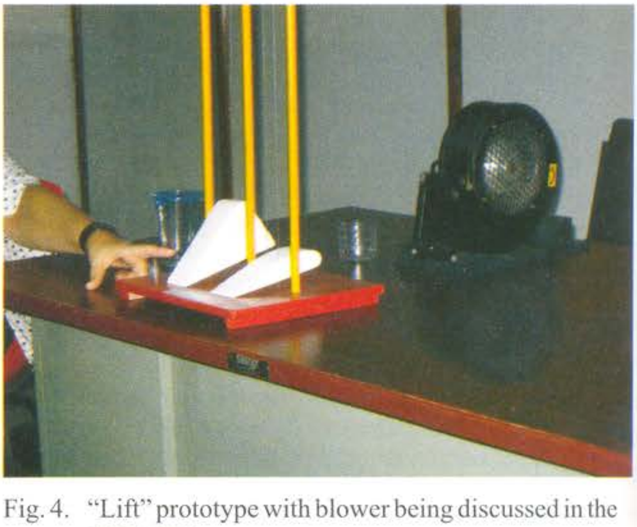


Fig. 4. "Lift" prototype with blower being discussed in the classroom.

"Lift" Prototype

The main problem with the original "Lift" component was that even if a visitor held the button to keep the blower on, it was hard to see much difference in how each shape was affected by the air current. We decided to use a small model, already built, that some of the students located in the central design offices. The model displayed two clearly different shapes attached to wires. The two shapes, one a wedge and one a curved wing, illustrated both "lift" and "drag" immediately, as the wedge remained stationery while the wing shape rose when a blower was trained on them. Using this model also gave us more time to focus on re-writing the labels and developing new graphics.

"Drag" Prototype

In the original "Drag" component the phenomenon was again subtle and difficult to notice. The students decided to carve several large Styrofoam shapes that a visitor could hold in front of a blower. They began with three shapes and then narrowed them down to two. Visitors (it was hoped) could experience "drag" (and even "lift") with their bodies as the forms reacted to the wind from the blower.

The Theory Behind the Practice

Below we discuss the theories and research underlying the changes the students made to the original exhibit as they developed their prototypes. As we watched them grapple with this iterative process, we could see them incorporating and applying new understandings into their own considerable life and work experience.

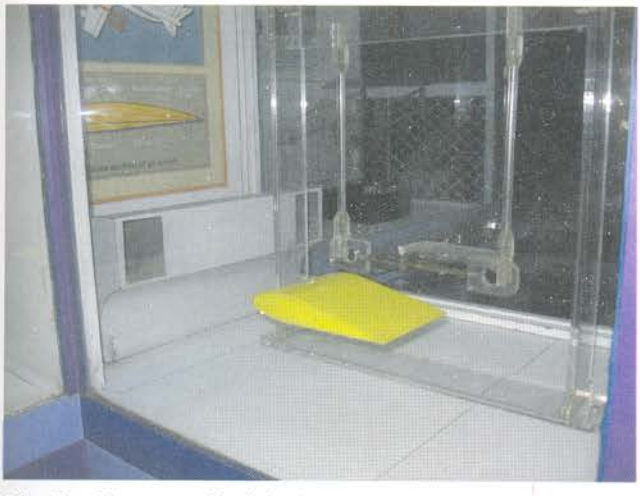


Fig. 5. Close-up of original "Drag" exhibit

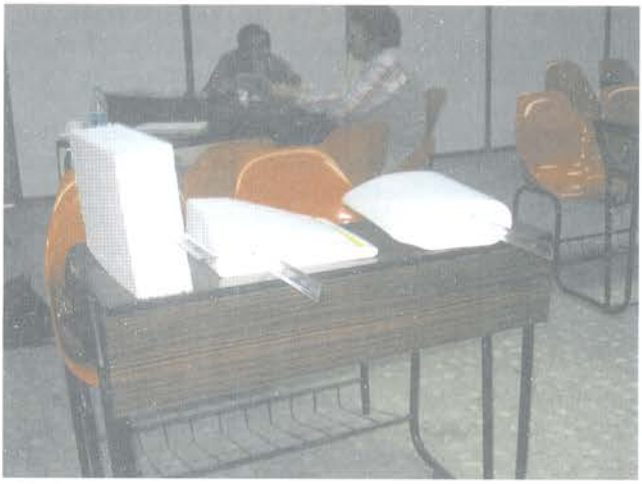


Fig. 6. "Drag" prototype forms (the middle one was eliminated from final prototype)

1. **The students had come to see that learning is change – the acquisition of new understandings, knowledge and skills – that can be measured[12].** Earlier we had had a number of interesting class discussions on a question raised by one of the students – is learning tangible or intangible? As part of the answer to this question, we read about and viewed video of a number of ingenious testing situations wherein developmental psychologists were able to observe and measure even young children's' acquisition of new understandings and knowledge – for example replications of Piaget's studies of children's' understanding of conservation of matter. We came to the conclusion that while the concept of learning may be abstract and intangible, the **effects** of learning, are tangible and measurable, even with children who may not be able to talk at

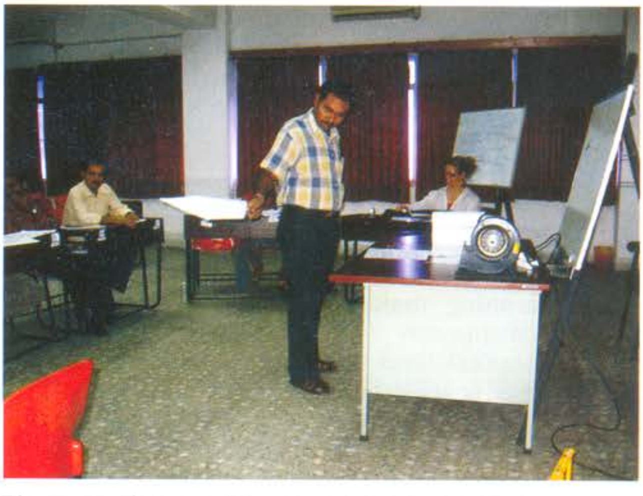


Fig. 7. Testing one of the "drag" prototypes in the classroom

length (or at all) about what they understand. It was with this understanding that we approached our visitor studies project.

The students grasped the importance of design (as well as content) for science communication in informal settings. They had read and discussed several chapters from a recent report by the National Research Council of the National Academies of Science in Washington, DC. Entitled *Learning Science in Informal Environments: People, Places, and Pursuits,* the report summarizes and analyzes the past 50 years of visitor studies, cognitive studies, developmental psychology, and a host of other disciplines as they relate to science learning in informal settings. An important theme of the report is that **museums are intentionally designed spaces; science exhibit design can be both a form of interpretation and a catalyst for science learning.** According to the report, exhibits that encourage science learning should:

be shaped by intentional design & personal interpretation (prior knowledge);
stimulate excitement, interest, & comfort;
feature direct experience and direct access to phenomena;
model scientific processes through interactivity; doing and seeing; meaning making and explanation (stimulate prior knowledge); questioning and predicting; self-reflection on learning;
be designed to encourage adult-child interaction[14].

The photographs of the prototyping process both in the classroom and in the museum gallery show that the students applied at least some of these principles, in particular, the idea that **design which takes into consideration visitors' levels of understanding and skills is a powerful interpretive tool.** The students were transformed by this insight and spent much of the class time designing a prototype to include visitors' prior knowledge of "lift" and "drag", to create interactivity, and to provide direct access to the phenomena they were trying to illustrate.

The students came to understand that learning is meaning making, an active process: "...the contemporary view of learning is that people construct new knowledge and understandings based on what they already know and believe[15]."

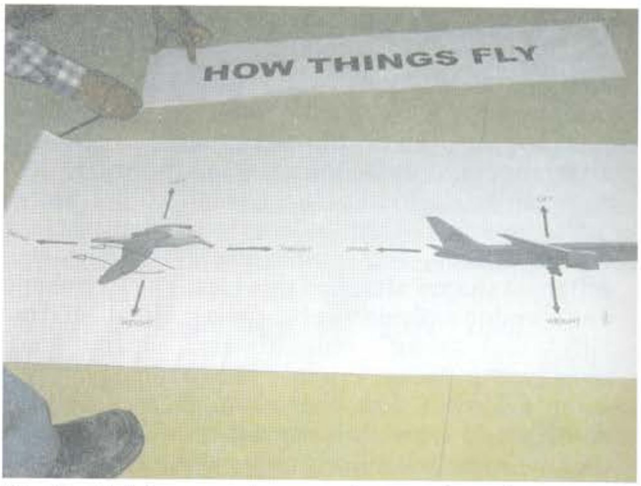
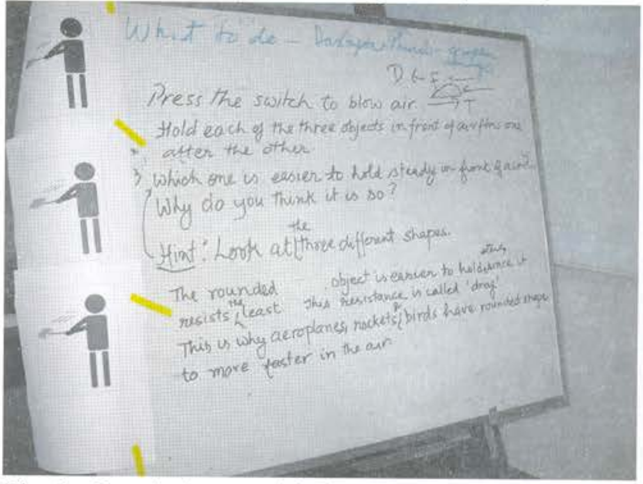


Fig. 8. Linking everyday experience to the science of flight

During observations and interviews, students became aware that many visitors had not flown before. So instead of relying on airplane-related examples, they discussed everyday experiences people might have had – experiences that would form their "prior knowledge" of the phenomena of "lift" and "drag": watching birds fly; flying a kite; feeling an umbrella "lift" in the wind or resist the wind; holding one's arm out against the wind from the window of a moving car; riding a bicycle or motorbike with clothes flapping, or wearing more body-hugging clothing; swimming with baggy or sleek swimwear.

The idea of creating large forms that visitors could hold – one a block that would pull back when held in front of a blower, and one shaped like a wing, that would remain more or less stationary as the blower air flowed over it – developed from these discussions of visitor prior knowledge, the efficacy of direct experience, and from the desire of the students to have visitors "feel" both "lift" and "drag", thereby connecting their past experience



What to do – [illegible]

Press the switch to blow air.
Hold each of the three objects in front of air flow one after the other
Which one is easier to hold steady in front of air?
Why do you think it is so?
Hint: Look at the three different shapes.
The rounded object is easier to hold steady since it resists the least. This resistance is called 'drag'.
This is why aeroplanes, rockets & birds have rounded shape to move faster in the air

Fig. 9. Developing new label copy was a challenge

with the scientific phenomena being explained. Related to this was another modification - to develop graphics demonstrating a range of everyday "lift" & "drag" experiences alongside the scientific concepts. As we discussed in class, "experience design" can help visitors connect what they already to know to ideas they are encountering for the first time[16].

4. **The students decided that the exhibit should have one Big Idea** that integrated the phenomena of "lift" and "drag". Guided by Beverly Serrell and her seminal work *Exhibit Labels, an Interpretive Approach*[17] the students decided that the big idea which brought the phenomena of "lift" & "drag" together was "how things fly". Interpreting one big idea often creates the cognitive space for people to connect in different ways to that idea which is a goal of learning in non-formal environments. One big idea also can support "sidebar" ideas, such as the variations of how things fly that the students wanted visitors to experience and feel with their own bodies.

5. **The students realized they would have to create various types of label copy:** Instructions on how to use each side of the exhibit From observing visitors, they noted that the original exhibits were not intuitive to use and even may have lead people to do or think the wrong thing. Striving for a more intuitive exhibit oftentimes includes clarifying the experience, using pictures to communicate and allowing for multiple outcomes[18]. Not all labels are instructions so it is important to visually distinguish instructive from contextual labels to help visitors engage and extend their experience New instructive labels like the one that said "push and hold" were placed directly at exhibit buttons, while a different color and location were selected for the placement of contextual labels and graphics.

A glossary The original exhibits introduced unfamiliar words and concepts so a glossary of terms was created to help decode these for visitors. "Lift", "drag", "velocity" and concepts like "angle of attack" were explained in glossary labels at each redesigned exhibit. Visitors could read them for general interest or refer to them when trying to figure out new concepts. Since one of the main goals of presenting science in informal learning environments like science.museums is to evoke pro-social behavior--specifically to engage people in broader discussion about science and technology in their daily lives--it is essential to give them the tools and sense of empowerment to do so[19].

Explanations that linked to visitor experience Current brain research suggests people who become successful scientific thinkers do so, in part, because they've learned how to make effective assumptions. The idea is that over time, individuals capable of making good scientifically guesses eventually learn how to normalize the process, which in turn leads them to conclude they are "thinking scientifically". As with so many other things in life, you are what you believe. The students tried to write labels that linked everyday phenomena to abstract concepts like "drag" with the hope that if people could relate to the umbrella experience, they could assume the more abstract ideas. However, writing labels that were easy to read and understand yet also explained scientific phenomena accurately and clearly, proved a difficult task. Moreover, some students still struggled to transform their own views about how much content a visitor needed or wanted in an exhibit label. Much debate, negotiation and eventually, collaboration occurred before acceptable labels emerged[20].

Fig. 10. Putting the prototype exhibit together at Science City.

Other characteristics that were considered when developing the labels included: type size and color, visual contrast, illustrations and diagrams. These technical factors have a very human impact when it comes to how visitors react to and perceive the exhibit[21] as do other aspects of visual, physical and intellectual accessibility. In class, students reviewed accessibility guidelines that are used in the United States, but these guidelines are not mandatory for Indian museums.

Testing the Re-Designed Exhibits

For those who may wonder whether exhibit prototypes can be assembled quickly and tested effectively with minimal time, take note of what our students accomplished! The night before final testing was to occur, we left them with a

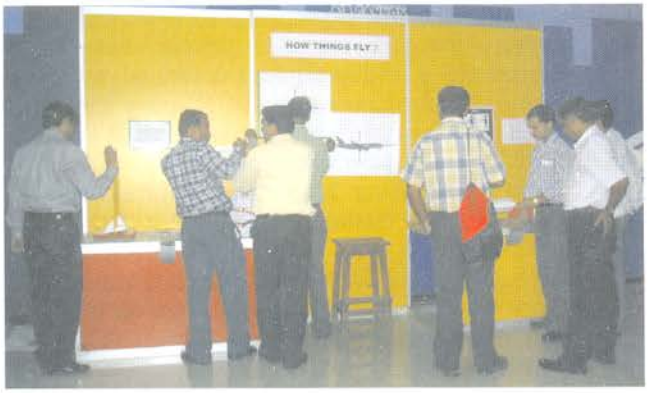


Fig. 11. Final touches to prototype.

number of assignments: complete the exhibit layout, print up large computer generated graphics and labels, find two blowers (one of the authors promised to bring her hair dryer just in case), find a wall with a plug where we could tack up our signs and plug in the blowers, etc. We weren't sure what we would find at Science City on testing day, when visitors would be coming to try to new versions of "lift" and "drag".

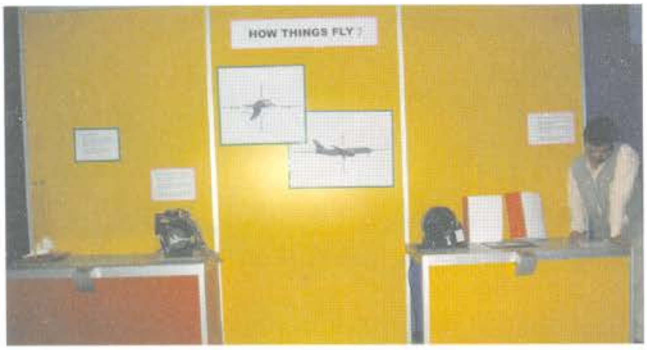


Fig. 12. The prototype exhibit ready for visitor testing.

When the authors arrived at Science City the next morning, we were impressed with the work that the students had done late into the night and early in the morning. The Fellows had created large graphic panels, including technical vocabulary, instructions for each interactive, and a large label for the entire exhibition. Several students who worked at Science City had located Mila walls and platforms, placed them near an outlet, found a second blower, and connected each blower to a red button for visitors to activate. The prototype exhibition was much more professional looking than anything we had anticipated. The students' teamwork and expertise had paid off.

Students from several Kolkata secondary schools had been organized by Educator Raju Manigandan of Science City and were waiting to try out the new exhibits. Photographs show the students and their teachers trying the exhibit while being observed and later interviewed by NCSM students. We had anticipated that the student visitors would be more knowledgeable about the principles of flight, and we were right. It would, of course, have been more scientifically useful if we had been able to test the new exhibits with the same number of family groups that had used it before. But we had to work with the usual visitation of most science museums – general visitors on weekends and school groups on weekdays. We were able to profit from the student visitors because we could observe whether or not they easily understood how to use the exhibits (most needed a bit of coaching). They seemed to enjoy the interactions. There were a few families visiting, and so were able to collect a small amount of data on family usage of the exhibit.

Debriefing the Prototyping Session

We were running out of time – we had only an hour or so at the end of the testing session to discuss our findings; our students had to get back to campus for further classes. But we did process the following from our morning's testing:

* Observations showed that students and families did try the activities, and seemed to enjoy them, but still needed coaching.

* Interviews revealed that visitor understanding of the new labels and activities was somewhat improved over the original exhibits, but not as much as we had hoped. Visitors (both the students and the families) still didn't know exactly what to do, and still didn't read the copy.

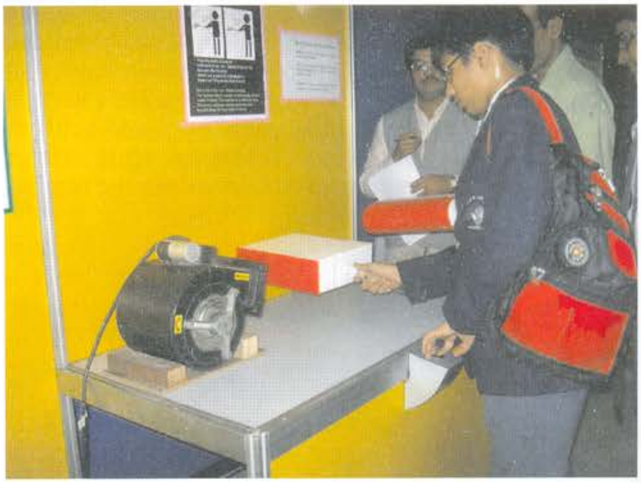


Fig. 13. A student trying the "Drag" exhibit, with observers behind.

* Interviews also revealed that the student visitors had been studying principles of flight in school; their familiarity with the phenomena and with the explanations from physics made them somewhat

impatient with our simpler explanations. This raised another question- might we need two levels of explanation?

- It may be that "lift" and "drag" are better understood in relationship to each other rather than as separate components. This would require thinking about how to perhaps integrate the two components into one.
- To really make the component engage visitors and involve them in doing the activities and reading the text, we would have had to do at least one more iteration, testing new label placement and explanations for how to use the interactive. Unfortunately, this was our last day of class, so it would not be possible.

Lessons Learned

What We Learned

We were inspired by our experiences on campus and in the museums and cities we explored during our time in India. We learned that we share a passion for exhibitions and a commitment to enhancing their education potential with our Indian colleagues, and that families everywhere face the same challenges when they embark on a museum visit. As with many museums in the United States, interest in incorporating the visitor voice is high but not yet fully incorporated into institutional culture. We learned that Science City and other NCSM museums attract vibrant audiences that bring many different kinds of science curiosities with them.

What We Think the Students Learned

By pairing *Learning in Non Formal Environments* with *Visitors Studies* in both theoretical and practical applications, we believe we succeeded in amplifying the experience for the MS students. Each component of the course energized the other – one goal was to demonstrate that individual staff members can enhance each other's role & results by a team approach. Another goal was to demonstrate that putting more focus on the learner will not diminish the curatorial role or the design role; it accentuates the skill each staff member brings because everyone works towards the goal of crafting a meaningful experience for visitors. We wanted to give the MS students hands-on experience with prototyping, label writing, visitor observation, visitor tracking, data synthesis, interpreting results, and learning to see an exhibition from the visitor's perspective. Their work during the project and their examination writings make us hopeful that they will retain and apply the following ideas in their museum practice:

- **Including the visitor voice need not be expensive:** It does not require hiring a professional evaluator or the use of expensive design techniques and materials. A great deal can be learned from simple, inexpensive prototypes that are observed, tested, and iteratively modified by museum curatorial, exhibits, and education staff.
- **Museum staff can work together to organize and create multiple ways to incorporate the visitor voice:** The students had four days of experience in a variety of visitor study techniques: observation; tracking; interviewing; developing simple modifications to existing exhibits. They also became familiar with existing visitor studies, such as the Borun family learning study, that can serve as models for future work.

Fig. 14. A mother and child at the "Lift" prototype

- **Family and multigenerational groups can and should be studied;** Too often visitor research is aimed at individuals; but research has shown that people all over the world tend to visit museums as multigenerational groups, and thus their museum experience is a social one[22].

- **Exhibits can and should be created to engage groups rather than individuals;** The prototypes developed by the students attempted to incorporate the seven elements of family-friendly exhibits. Museum professionals sometimes dismiss the knowledge and skill needed to effectively connect families and exhibits[23]. Our students understand the payoffs that will come from their persistence.

- **Including the visitor voice takes time, planning and trust**: Museum staff can do this but they must be allowed the time and space to set up, conduct, and process prototyping, observing, and conversing with visitors. Colleagues may also need time to learn to trust that visitor input is valid.

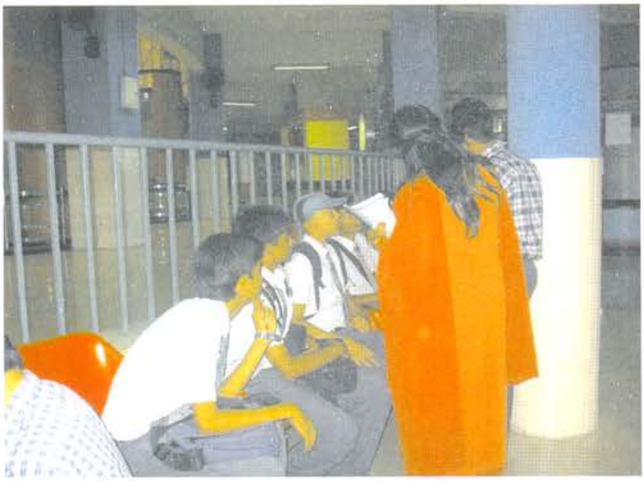


Fig. 15. NCSM students (standing) interviewing students who had tried the prototype

NCSM and Incorporation of the Visitor Experience

NCSM's encouragement of our visitor studies project and its integration into the MS program indicates to us a commitment to increased inclusion of the visitor voice in museum practice. This is an important step toward implementing further studies and resources required to ensure that conversations with visitors and utilization of their perspectives in museum, exhibition, and program design are part of the long range planning of the organization.

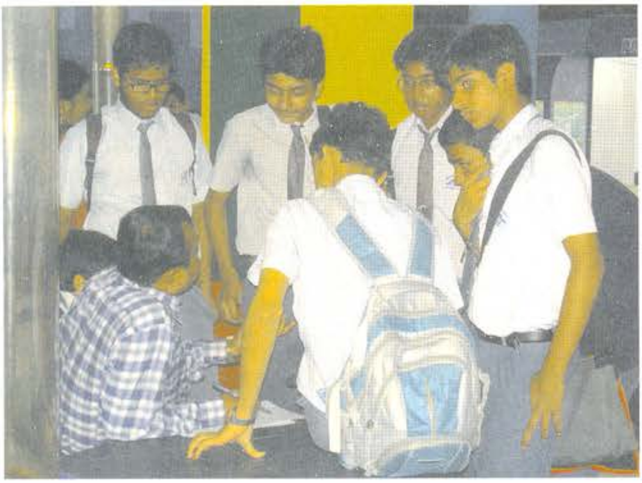


Fig. 16. NCSM student talking with local student testers of the prototype

NCSM and Incorporation of the Visitor Experience

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Acknowledgements

We wish to thank Science City's Director Arijit Dutta Choudhury for giving us permission to use the museum as our teaching/learning laboratory and Raju Manigandan, formerly with Science City and now Project Coordinator at the North Bengal Science Centre, for scheduling students to test our prototypes.

Fig. 17. The authors and their students: Front row, left to right: B. B. Srivastava; K.S. Murali; N. Dasgupta; K. Lee; G. Jennings; S. Majumder; P. Grover; S. Chaudhuri. Back row, left to right: R. Das; K. K. Singh; S. Chakraborty; V. Subhaprada.

APPENDIX-A

"LIFT" QUESTIONNAIRE

1. In your own words, explain what "lift" is?
2. When you used the exhibit, did you push both buttons? What happened? Prompt: Did you see a difference?
3. Do you think the shape of the two objects (in the case) affects how they move? Explain.
4. Do you see a connection between this exhibit and how an airplane flies? Explain.

"DRAG" QUESTIONNAIRE

1. In your own words, what is "drag"? Prompt: Did you use the exhibit, see something occur?
2. Did you push both buttons? What happened? Prompt: Did you see a difference?
3. Did the shape or orientation of the two objects you watched (prompt: a yellow one, a clear, flat one) affect how they moved when the air hit them? Explain.
4. Do you see a connection between this exhibit and how an airplane flies? Explain.

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The Making of India's First Short-Length Sustained Foucault Pendulum and the New Design

E. Islam

Abstract

Because of their elegant looks, emotive appeal and profound educational implications, many shorter and improved versions of the Foucault pendulum have found their ways into the hallways of famous government buildings, central lobbies of universities and the foyers of some of the world's best science museums. However, none was to be found in India till very recently. The article describes the first successful Indian attempt in building a short-length sustained Foucault pendulum at the Central Research & Training Laboratory of the National Council of Science Museums (NCSM).

Construction of a Foucault pendulum and its successful installation poses many daunting problems. Its performance is delicately dependent on various factors; some are intrinsic parameters of the design and some are due to external influences. Different designs have been tried world-over for better performance and long life of the pendulum. The first Indian effort succeeded in incorporating novel features in the pendulum's suspension system resulting in enhanced accuracy. The new design also got a patent cover for its innovative features.

Introduction

The earth rotates about its polar axis once in nearly 24 hours, resulting in the cyclic occurrence of days followed by nights. It is a phenomenon so matter of fact that we hardly demand a direct experimental proof for this celestial clockwork. However, can a terrestrial experiment be designed for a direct & quantitative proof of the planet's rotational motion?

Fig. 1. Leon Foucault (1819-1866).

In 1851, a wonderfully simple but ingenious experiment carried out by the famous French physicist Leon Foucault (Fig. 1), provided the first direct proof of the rotational motion of the earth. His celebrated pendulum experiment is held in reverence by physicists and astronomers as one of the brilliant experiments of all time. Successive pendulum experiments that replicated or improved upon Foucault's pioneering efforts came to be known as 'Foucault Pendulums' after the great inventor's name.

Although Leon Foucault's original experiment was a novel work, the set-up he used was not suitable for continuous observation and the results obtained lacked in quantitative accuracy.

Foucault Pendulum: Historical Background

The Foucault pendulum was invented by accident, and any description of a Foucault pendulum is incomplete without a brief anecdotal reference to this fortunate 'accident'.

In 1848 Leon Foucault was setting up a long, skinny metal rod in his lathe. He accidentally 'twanged' it, and the end of the piece of metal proceeded to go up-and-down. The rod continued to vibrate in the same plane while the chuck rotated its fixed end. This set Leon Foucault thinking. He suspended a short pendulum from the chuck of a vertical drill press, set the pendulum oscillating, and then started the drill press. Once again, the pendulum kept swinging in its original plane, and ignored the fact that its mounting point was rotating. That very moment Foucault came to know for sure he had a system that maintained its orientation even in a rotating frame.

He went on to construct a 2 metre-long pendulum with a 5 kilogram ball in his workshop and set it in motion. Before the amplitude of its swing died away, which it did very quickly, he could see that the weight on the end of the pendulum appeared to rotate clockwise very slightly. He knew that observation over a longer period was necessary to be sure of the apparent clockwise rotation of the pendulum's plane of oscillation. He then built a second pendulum with an 11-metre long wire and put it in the Paris Observatory for observation. It too rotated clockwise.

Foucault had no doubt left in his mind that a sufficiently long pendulum would be able to demonstrate the rotational motion of the earth clearly. And he decided to construct a really long one.

A 62 pound cannon ball held by a 200 feet long piano wire constituted his pendulum. The fact that a long pendulum would sustain its oscillation for longer and that a heavy one would be more immune to external disturbances led Foucault to design such a huge pendulum, which required nothing less than the dome of Pantheon to be hung from (Fig. 2). He also took great care to make sure that the wire was perfectly symmetrical in its metallurgy. When the pendulum was hung, a sand bed was made over an area just below it, and a stylus was touched the sand. For setting the pendulum in motion, the bob was pulled to one side and tied in place with a thread. When the system settled, the thread was burned. The pendulum made true sweeps, to and fro, while the stylus traced straight lines on the sand bed. The pattern gradually grew in a clockwise direction, and at the end of an hour the line had turned 11 degrees 18 minutes. The only reason was, Foucault argued, the earth had turned beneath the pendulum while the pendulum's plane of swing simply refused to do so. He was, as he put it later, was seeing the earth spinning around.

Fig. 2. The Pantheon in Paris

The success of the experiment caught the fancy of nineteenth century Europe and was repeated with varying degree of success at Cologne, Reims, Amiens, St. Jacques and elsewhere where towers of great heights were available for doing the experiment.

Many experimentalists have since then developed shorter and improved versions of the Foucault pendulum for sustained operation and greater accuracy of performance in respect of their ability to measure the rotational rate of the earth. These pendulums, because of their elegant looks and profound emotive & educational implications, have easily found ways into the hallways of famous government buildings, central lobbies of universities and the foyers of some of the world's best science museums. Famous examples are the UN building in NY and the Deutches Museum in Munich. However, while most of these experiments have been designed and displayed in the western world, none has so far been reported as a successful Indian venture prior to the one this article describes.

Genesis of the First Indian Attempt

The first Indian attempt to develop a self-sustained Foucault pendulum had to wait, for reasons quite inexplicable, until 1991 when a request for indigenously developing one was received by Dr. Saroj Ghose, the then Director General of the National Council of Science Museums (NCSM) from none other than the noted astrophysicist, Professor J V Narlikar. He was then finalizing the architectural plan for his new institute, the Inter-University Centre for Astronomy and Astrophysics in Pune. He wanted to have a performing Foucault pendulum to adorn the central lobby of the new building that was to carry the hallmark of a Charles Correa design. What could have signified the objective of an institute on astronomy and astrophysics better than a shining sphere of metal, elegantly hung by a long wire and ceaselessly swinging back and forth over the central court while changing its plane of swing continuously? The system could serve as a testimony to the spin of the earth and hence was an apt choice that could set the underlying tone of the institute – to demystify the heavens.

The NCSM accepted Prof. Narlikar's request, and with this the seed of India's first Foucault pendulum was sown.

Building up the Theoretical Framework

A team under the leadership of Mr. Ingit Mukherjee, the then director of NCSM's Central Research & Training Laboratory (CRTL) at Salt Lake, Kolkata was formed which was made responsible for the design and development of the pendulum. Being a member of the team, the author of this article was witness to the painstaking and often frustrating efforts that underwrote the making of the first Foucault pendulum in India.

We began with no prior knowledge about the design considerations for a short-length driven Foucault pendulum system. Hence we first decided to study available literature to obtain a preliminary parametric guideline as to how to proceed to actually construct a Foucault pendulum. The questions we asked ourselves were:

What would be the theoretical value of the earth's rotational rate at Kolkata where the experiment was to be conducted? How much would the pendulum's apparent rate of rotation vary from the theoretical value due to design parameters? What environmental factors would influence the performance of the pendulum? What were the crucial design considerations? How much error would be considered acceptable?

The result of our studies was tabulated, which provided a broad theoretical framework and served as the launching pad for our work.

Physics of the Foucault Pendulum

Foucault pendulums demonstrate earth's rotation while normal pendulums do not. Why?

Anything that is fixed to the earth by either mechanical means or by the pull of gravity is also carried along with its rotational motion. In order that earth's rotation is detected by a terrestrial experiment, one needs to have a system which has some measurable parameter that remains invariant under the rotation of the earth. This would mean that the experiment must use a set-up, which despite being held in the earth frame, is capable of effectively freeing itself from it. By definition, a simple pendulum does accomplish the task once it is set swinging freely. Let us examine why this happens.

In order to change the simple pendulum's plane of swing, a torque is needed to act on the plane about its support. This would require two things: an external force having a non-zero component at right angle to the plane of oscillation, and a position away from its axis on the pendulum's plane where the external force could be applied. Both these requirements are not met in the case of an ideal simple pendulum. Considering the suspending wire to be perfectly flexible, there can be no moment due to bending of the wire. Also, since there is no friction at the support, no moment due to frictional forces exist about the support. Thus a swinging pendulum is acted upon by only two forces, namely, the tension of the string and the gravity force (neglecting air friction and other external noise). None of these two forces has any moment about the axis of the pendulum. Moreover, since an ideal simple pendulum is held by a single point support, there exists no point on its plane away from the axis where an external force, even if it existed, could be applied to yield a non-zero moment about the axis. Hence it is easy to appreciate why the plane of oscillation of an idealized simple pendulum would become invariant under the rotation of its support.

If a pendulum is designed to effectively behave as an ideal simple pendulum by removing the possibility of asymmetric forces affecting its motion, a Foucault pendulum will have resulted. For a Foucault pendulum designer, understanding how asymmetric forces could creep in the system is of paramount significance for being able to deal with it during both design and fabrication stages.

If the internal structure of the wire is such that it cannot bend with equal ease in all radial directions in its cross-section, the plane of swing of the pendulum would seek a preferred direction in which the wire can bend with maximum ease, and would thus be carried by the rotating earth instead of being fixed in space. Also, the manner in which a practical pendulum is held is of immense importance because an asymmetric support structure may lead to a preferential or a fixed plane of swing. An asymmetric support is one that does not hold the wire equally rigidly from all sides, and thus introduces unequal radial flexibility for the wire at the support point. Such departures from ideal conditions may introduce varying periodicity in different planes of oscillation, which eventually makes the pendulum execute elliptical motion instead of true sweeps.

Overcoming these limitations for a practical pendulum is a daunting task. To make a practical design mimic the attributes of a theoretical pendulum is a challenge even to the accomplished engineers – a reason why we make pendulums everywhere, but Foucault pendulums very rarely.

Apparent Turning Rate: Latitudinal Variation

A Foucault pendulum's apparent turning rate at any place on the earth's surface would necessarily be equal in magnitude and opposite in sense to the angular rotation of the earth about the vertical at that place. We derived a general expression for the earth's rotational rate about the vertical at any latitude using the geometrical construction given in Fig. 3:

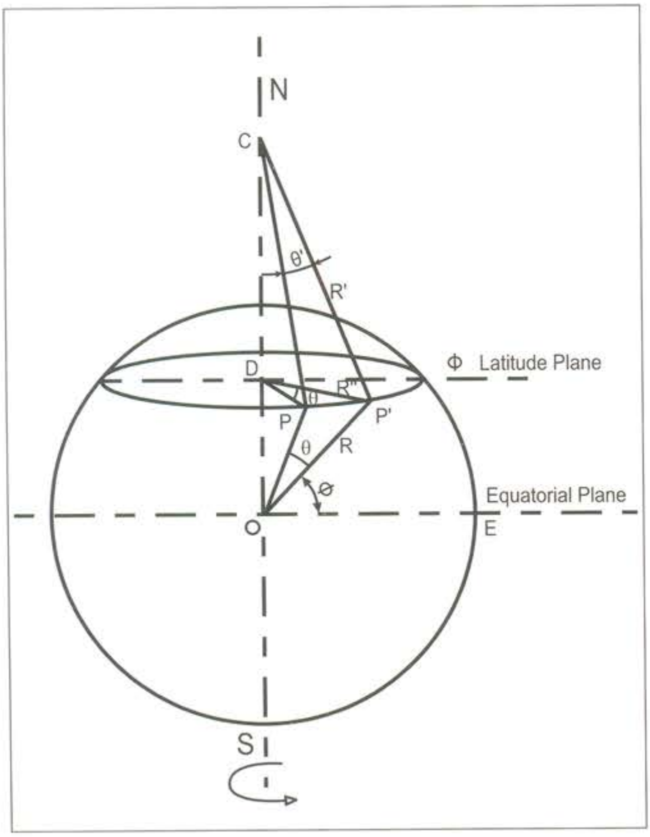


Fig. 3.

f : Latitude angle of the place P, P'...

q : Angle swept in the latitude plane of P, P' by the displacement of point P to P' due to earth's diurnal rotation.

q' : Angle traced by the tangent plane CP by the displacement of P to P'due to the rotation of earth. [This is the angle which the pendulum's plane of oscillation would appear to rotate with respect to the observer at P, P' over time 't' during which P is displaced to P']

From the diagram:

i) Đ POE = Đ P'OE = f (latitude at PP') = Đ OCP = Đ OCP';
ii) OP = OP' - R, radius of Earth;
iii) DP = DP' = R'', radius of latitude circle (=R cos$f$);
iv) CP = CP' =R', slant height of tangent envelope cone.

Ø : Latitude angle of the place P, P'...

θ : Angle swept in the latitude plane of P, P' by the displacement of point P to P' due to earth's diurnal rotation.

θ' :Angle traced by the tangent plane CP by the displacement of P to P' due to the rotation of the earth. [This is the angle which the pendulum's plane of oscillation would appear to rotate with respect to the observer at P, P' over time 't' during which P is displaced to P'].

From the diagram:

i) ∠POE = P'OE = Ø (latitude at PP') =∠ OCP = ∠ OCP';
ii) OP = OP' = R, radius of Earth;
iii) DP = DP' = R'', radius of latitude circle (=R cosØ);
iv) CP = CP' = R', slant height of tangent envelope cone.

Derivation:

Length of arc PP' = R'' θ = R' θ' (permitted for small θ') .... (1)

In Δ DPO, ∠OPD = Ø, ∠D = 90° and hence $\frac{R''}{R}$ = Cos Ø, or R'' = R. Cos Ø ....(2)

Putting **(2)** in **(1),** we get $\theta' = \left(\frac{RCos\varnothing}{R'}\right)\theta$ or

$\frac{d\theta}{dt} = \left(\frac{RCos\varnothing}{R'}\right)\frac{d\theta}{dt}$ ....(3)

In Δ CPO, Tan Ø = $\frac{R}{R'}$; or R = R' Tan Ø.........(4)

Substituting **(4)** in **(3),** one gets $\frac{d\theta'}{dt}$= (Tan Ø CosØ) $\frac{d\theta}{dt}$;

or $\frac{d\theta'}{dt} = \text{Sin}\varnothing\frac{d\theta}{dt}$ ....(5),

which gives the general expression for the rotational rate at any place having latitude angle Ø. Earth's rotational rate $\frac{d\theta}{dt}$ about its polar axis being equal to 15^0/hour, an expression for the Foucault pendulum's apparent rate of rotation at any latitude Ø is obtained from equation (5):
w (Ø) = 15^0 x sin Ø per hour ....(6) (sense being clockwise in northern hemisphere and anticlockwise in the southern hemisphere).

One could also arrive at (6) from a physical consideration of the system (Fig. 4).

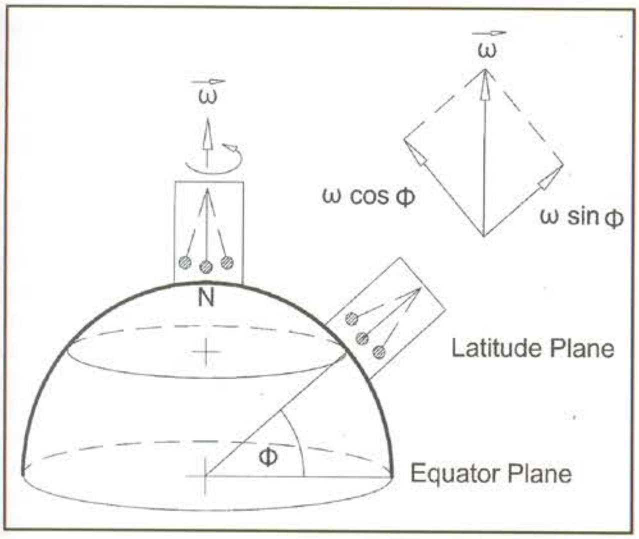


Fig. 4.

If $\vec{w}$ denotes the angular velocity vector of the earth about its polar axis at the North Pole, then $|\vec{w}|$ 15°/ hour (anticlockwise). At any latitude $\emptyset$, the projection of $\vec{w}$ on the local vertical is $\vec{w}(\emptyset) = \vec{w} \sin \emptyset$. Here a Foucault pendulum's apparent rotation is $|\vec{w}| \sin \emptyset = (15° \text{x} \sin \emptyset)$/ hour (clockwise). In terms of the time **T**$'$ taken by the pendulum to rotate through 360°, equation (6) above can be rewritten as:

$$T' = \frac{360^{\circ}}{15^{\circ} x \sin \emptyset} \text{ hrs} = \frac{T}{\sin \emptyset} \text{ hrs} \quad .....(7),$$ where T is the period of earth's diurnal rotation.

At the poles: $\emptyset = 90°$, $w(\emptyset) = 15°$ (from equation 6), or the rate of apparent angular rotation of a Foucault pendulum at the poles will be maximum and equal in magnitude to the Earth's rate of rotation about its polar axis.

At the equator: $\emptyset = 0°$, therefore $w(\emptyset) = 0$ (from equation 6), which means a Foucault pendulum installed at the equator will not show any apparent rotation of its plane but instead will be carried along by rotating earth.

Effect of Design Parameters on Turning Rate

If 'a' and 'l' denote the amplitude and the length of the pendulum respectively, then it can be theoretically derived that equation (7) above gets modified as

$$T' = \frac{T}{Sin\,\emptyset} [1 - (3a^2/8\,l^2)] \quad .... (8)$$

However, another modification in the above expression becomes necessary due to the constructional parameters of the 'Charron Ring', a very important component of the Foucault pendulum system that will be discussed later. Finally we have the following modified equation:

$$T' = \frac{T}{Sin\,\emptyset} [1 - (3a^2/8\,l^2) - (4d/\pi a)] \quad .... (9)$$

where, a = amplitude of swing; l = length of the pendulum; d = annular spacing at the Charron ring.

Equation (9), therefore, provides the theoretical benchmark for judging the performance of our proposed pendulum. This, however, excludes possible perturbations to the pendulum's motion due to external noise like vibration of support structure, air current or presence of strong magnetic field etc.

Our Failed Experiments

With the necessary theoretical background in place, we were in a position to actually start the design and fabrication work in the mechanical workshop of the Central Research and Training Laboratory at Salt Lake, Kolkata. The workshop had an area with double floor height, which could accommodate a length of about 20 feet that we thought was a workable size for our first attempt.

Three subsystems are important for any pendulum set up:

a) pendulum itself (wire and the heavy bob)
b) suspension or support structure
c) driver unit

In addition, precise alignment of the subsystems along a vertical axis is crucially important. The suspension point, the suspension wire, the centre of gravity of the bob, the centre of the driving force field- all must lie along the same vertical line.

First Attempt

Initially we used for the pendulum bob an iron ball of about 100 mm in diameter and approximately 4 kilos in weight (We had the ball in our workshop and used it for the 'shot put' event during our annual sports). It was hung by an 18 feet long, single strand 18 swg GI wire of the common type.

For the suspension unit, we turned a 50 mm long piece of a 62 mm dia brass rod in the lathe and drilled a hole through it which could just accommodate the diameter of the wire without any visible slackness. We tapered off one end of the wire and passed it through the hole forcibly until about a couple of inches of it protruded out at the opposite end. The tapered portion was cut off and a lump of metal was then brazed at the tip such that the wire would not slip back through the hole under the weight of the metal attached to the other end of the wire by means of a hook welded to it. The brass piece holding the upper end of the wire was screwed to a 6 mm thick mild steel plate, which in turn was fixed to the ceiling.

For the driving unit, we used an electromagnetic driving system, which basically consisted of an electromagnet, and an electronic control circuit that ensured that the electromagnet was energized only when a magnetic or a conducting body passed over its centre. All the three subsystems were aligned to the best of our ability and the set up was ready for a trial run.

For checking the expected rotational motion of the pendulum, a reference court with graduation marks at every 5^0 interval was placed centrally just below the ball. A hole that easily allowed the pole piece of the electromagnet was made exactly at the centre of the court made of plywood. The electromagnet was kept below the court in such a way that its pole piece just flushed with the surface of the court. For starting the pendulum, we followed a procedure widely prescribed in the literature. The metal ball was pulled to one side and was held in this position with the help of a cotton thread that tied the ball to a fixed post. When the system became still, the thread was burned. The ball started moving to and fro passing over the central pole piece.

The pendulum appeared to execute, to our delight, true sweeps, but only initially. Within about ten minutes time its amplitude decreased visibly and the pendulum started to move elliptically. The minor axis of the ellipse grew quickly resulting in almost a circular motion about the central pole piece and ultimately the pendulum stopped.

Second Attempt

Keeping all other components intact, we replaced the iron bob with one made of brass and then glued to its bottom a ceramic magnet of one-inch diameter. A circular undercut was made in the lathe for properly locating the ceramic magnet at the exact centre of the bottommost part of the pendulum such that the suspension wire, the centre of the bob, the centre of the ceramic magnet and that of the electromagnet – all fell in the same vertical axis. We then started the pendulum all over again and waited with baited breath.

The oscillations showed no sign of dying down even after 15 minutes, and to our delight, its plane also visibly moved away from the direction in which we had left it alone. Taking reference of the graduated court over which the pendulum moved, we started noting down the turning rate every 15 minutes. Our readings gave a rate that was higher than the theoretical value of 5.8^0 per hour calculated for Calcutta's latitude. The observation was disturbing, but we decided to wait and watch. Further readings during the next couple of hours brought new surprises - the pendulum turned increasingly faster and also performed ellipses instead of linear sweeps. We left the pendulum 'on' overnight. At 10 o'clock next morning when we resumed our observation, a kind of shock greeted us. Even after almost 16 hours, it has made a ground of only about 20 degrees, lagging behind the theoretical value by a whopping 76 degrees. While we started thinking about the possible reasons for the failure, we allowed the pendulum to run as long as it could, hoping to at least assure ourselves that the driver system worked.

But more shocks were in the offing. The pendulum's plane refused to shift from where it had been at 10 a.m. We had no idea of what had happened between 6 p.m. in the previous evening when it was tuning faster than expected, and 10 a.m. that morning when it stopped turning altogether, although it continued to swing in this fixed direction maintaining constant amplitude.

Apprehending that the alignment of the suspension unit with respect to the vertical at the point of suspension might not have been proper, we stopped the pendulum and went up to the ceiling, and realigned the suspension unit with as much precision as we could. The centering of the electromagnet and the ceramic magnet at the bottom of the bob was rechecked and the pendulum was then restarted in a direction different from the one in which it got fixed. The plane apparently shifted clockwise again, its rate this time slowing down with time in contrast to the previous experience, and after about 5 hours of strenuous journey in the same direction, it gave up. The pendulum stopped changing its plane of swing and remained fixed in a particular direction different from the earlier case. In order to find out the preferred sectors over which the pendulum turned either faster or slower, we restarted its swing in a direction a few degrees further away in the clockwise sense hoping to ease the pendulum out of the preferred direction in which it was trapped. We retired for the night and came back next morning hoping to see the pendulum leave a trail of why it had been behaving so mysteriously.

But the pendulum was gone. Together with the entire length of the wire coiled around in inanimate stillness, the heavy bob laid crestfallen on the edge of the court in deadly silence. We too missed a few beats at the premature demise of our pendulum.

The wire snapped just below the brass holder of the suspension assembly. We now had an additional jinx to get level with. Survival of the suspension wire for a considerable period was a fundamental prerequisite that must be ensured if we were to meet with any possible success in future.

Learning Points

We had these challenges to meet:

* Preventing premature snapping of the wire and ensuring long life of the pendulum.
* Redesigning the suspension assembly to ensure not only a long life for the wire but also to prevent the pendulum from seeking preferred direction. Because if it did, the wire would undergo continuous flexing along a fixed line in its cross section and will eventually snap.
* Arresting or eliminating the tendency to perform ellipses instead of linear oscillations.

We decided to experiment with various types of stainless and spring steel wires available in the market, although we knew that no wire would be able to sustain millions of flexing operations in one direction. Here lies the importance of prohibiting the pendulum from seeking a preferred direction for its plane. I am tempted to dwell a little more on this issue of crucial importance and would seek the reader's attention to the explanatory illustration (Fig. 5).

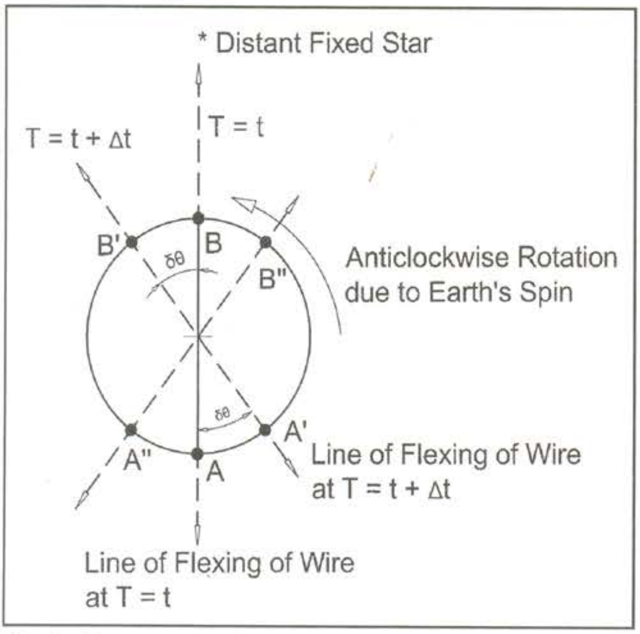

* Distant Fixed Star
T = t + Δt
T = t
B'
δθ
B
B"
Anticlockwise Rotation due to Earth's Spin
δθ
A'
A"
A
Line of Flexing of Wire at T = t + Δt
Line of Flexing of Wire at T = t

Fig. 5. Cross-sectional view of wire.

Consider a cross-section of the wire at the point of suspension. Suppose at time $T = t$, the wire flexes along the line AB pointing to a fixed direction in space. An infinitesimally small instant later at $t = t + \delta t$, the wire turns anticlockwise along with the earth by say, $\delta\theta$ moving the line AB to $A'B'$. Now for a Foucault pendulum, the plane of swing would remain invariant under the earth's rotation, which means that at $t + \delta t$, a new line $A''B''$ would be brought by the rotating earth along the spatial direction pointing to the same fixed star. And again after an interval δt, another new line in the pendulum's cross-section would fall along the plane of swing.

In Calcutta the pendulum would take about two and a half days to make a complete rotation. Therefore if our experimental system performed as a Foucault pendulum, the wire would flex along any particular direction in its cross-section only once in two and a half days. On the other hand, if the pendulum's plane of swing would get fixed with respect to the earth frame instead of the space frame, then any particular line of the wire's cross-section would flex about 100,000 times during the same time. That is to say that the life of the wire would be 100,000 times more if it supported a pendulum performing as a Foucault pendulum than if it worked as a normal pendulum.

Relooking at Some Crucial Features

Suspension System

The above analysis at once convinced us to focus our attention more on the suspension system, which mostly determined whether the pendulum would be able to oscillate equally freely in all possible directions. Achieving an absolutely symmetric rigid support was the key factor for success.

But we honestly had no idea how to proceed further. We surveyed available technical literature on the subject and get hold of a few that reported the suspension unit in some detail.

Of all the successful designs, the one developed by Philips for supporting the pendulum at the entrance hall of the UN Headquarters in New York was the most reported.

The central features of their system were: the use of a universal joint for ensuring equal radial flexibility of the wire it held. The next well known system we came across used a four-jawed chuck for holding the wire equally rigidly from all sides. Among the other less known, the double knife-edge supports were reported to have worked if constructed perfectly. We chose to go for the incorporation of a universal joint in our new system.

The Problem with Elliptical Motions and the Importance of Charron Ring

It was essential to incorporate a system in our future design which would arrest the pendulum's tendency to undergo elliptical oscillations. Otherwise the pendulum's plane of swing would undergo precession on its own, and hence would make precession due to earth's rotation immeasurable.

We undertook elaborate theoretical exercises to get to the root cause of the observed elliptical motions. On a simplistic note, it might be said that ellipses instead of straight-line motion for a pendulum would occur if it had different periodicity of swing in different directions, imparted by imperfections in the structure of the wire, unequal rigidity and lack of absolute symmetry in the support, perturbations due to external influences like air current and also presence of magnets or ferromagnetic substances in the vicinity of the bob (because it had a permanent magnet at the bottom) or near the electromagnetic driver unit.

We knew that complete elimination of the above reasons for elliptical motion was not possible and hence we could only attempt a curative measure and not a preventive one. Fortunately, we came across the so called 'Charron Ring' system used by Philips for its pendulum at the UN building in NY, which had a carefully centred metal ring just below the support structure through which the wire passed and rubbed against twice in each swing.

Named in honor of M.F.Charron, a French physicist who first derived it, the Charron system of suspension is a simple method of overcoming the "ellipsing" problem. The following diagram illustrates the system (Fig. 6a & 6b).

At a distance l' below the point of suspension A (see figure 6a) Charron fixed a metal ring B having an internal diameter slightly larger than the thickness of the pendulum wire, leaving an annular spacing of *d.* As soon as the deflection of the bob exceeds the value $\frac{ld}{l'}$, the wire touches the ring and the point of contact then functions as the "point of suspension". The consequence is that the minor axis of an elliptical orbit which may have been forming is rapidly diminished. With reference to the figure 6b below, this can be roughly explained as follows.

Assuming that the wire, as long as it does not touch the ring, is straight, it will describe at the level of the ring an ellipse geometrically similar to the elliptical orbit of the bob reduced in the ratio $\frac{l'}{l}$.

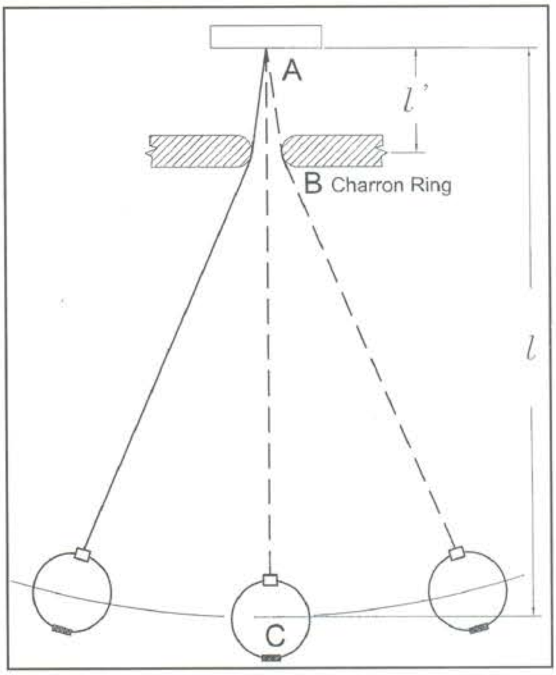


Fig. 6a. Charron's suspension system.

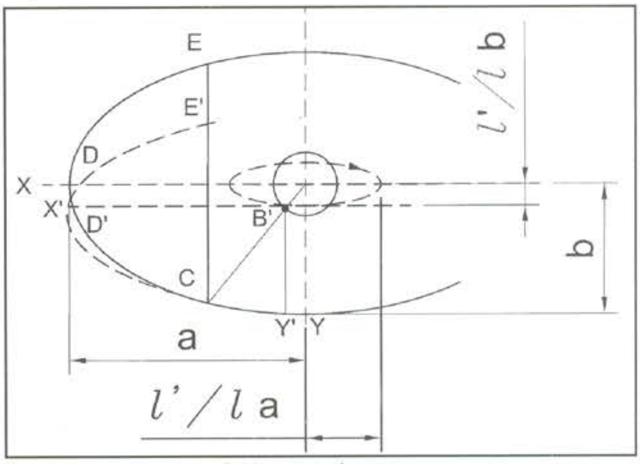


Fig. 6b. Function of Charron ring.

We see, then, that the amplitude in the Y direction at the beginning of the following half-swing has been reduced by the distance EE', which is approximately equal to $\frac{2bl'}{l}$. The relative reduction for each full swing amounts to $\frac{\Delta b}{b} = \frac{4l'}{l}$, where Δb = the decrement in the minor axis of the ellipse due to Charron ring. It has been tacitly assumed in the foregoing that while the bob describes the orbit $CD'E'$ the wire stays pressed against the ring at point B'. As a rule the contact friction will not be sufficient for this to occur. In reality, therefore, $\frac{\Delta b}{b}$ is smaller than calculated here, but this does not alter the fact that the mounting of the ring is a very effective means of combating the elliptical motion. Charron deduced that the use of this construction would slightly shorten the expected period of rotation of the pendulum's plane given by the factor $(4d/\pi a)$ in Equation (9) stated earlier.

Elliptical motion in a freely swinging pendulum is accompanied by an intrinsic precession of angular velocity $\omega = \frac{3A}{4l^2T}$, where A is the area of the ellipse (path of the bob projected onto the horizontal plane), l is the length of the pendulum, and T is the period. The sense of the precession being the same as that of the elliptical motion, the effect is strong: for example, for a pendulum of length 2 m and amplitude (centre to extremity) 0.2 m, the intrinsic precession rate will be equal to the Foucault turning rate (at 40° latitude) if the minor diameter of the ellipse is 2.2 mm. For the error to within 20%, which many consider tolerable, it would have to be less than half a millimetre, an amount scarcely perceptible to the eye.

Thus we found that the problem of the precession due to elliptical motion rapidly become more serious as the length of a Foucault pendulum is decreased to about a few metres, roughly the kind of length we were experimenting with. Hence the use of a perfectly designed Charron ring became absolutely necessary for us.

Modified Experiment That Also Failed

Our next experimental set-up was a more enlightened effort aiming to make use of all the knowledge we gathered in the meanwhile. We changed the suspension system to incorporate a universal joint (of the type readily available in the market), put a Charron ring (as a separate unit) a little below the point of suspension of the wire, used a length of a new and fairly straight 18 swg s.s wire. We used the earlier driver unit because it worked well. And thus, after almost a period of two months, our next set-up was put on test run at the same site. The swing attained and sustained its target amplitude sweeping over the court back and forth ceaselessly in what looked like true oscillations. In fact the pendulum did everything right except doing what it was made for – its plane remained as flat-footed as a stubborn child on his way to school.

I could hardly accept the construction would have gone wrong and instead would vouch that the alignment of the different subsystems viz. the suspension assembly including the universal pivot, the Charron ring, the bob with the magnet and the electromagnet, might not have been proper and required readjustment. I went up to the ceiling and watched carefully how the universal joint was doing. I noticed that the pendulum's fixed direction of oscillation fell in line with the free direction of motion corresponding to the bottom pair of bearings in the universal joint. It occurred to me that the universal support system for the pendulum was not as free in other intermediate directions as it was in the two mutually perpendicular axes in which its two pairs of bearings were mounted. In order to check my suspicion, I stopped the pendulum and restarted it in an intermediate direction between the two free axes of the bearings. The result was revealing. The pendulum's plane of swing started moving in the right direction, developed narrow ellipses whose temporal growth lacked wide variation in the dimension of the minor axis (as was seen in earlier attempts), and ultimately stopped shifting any further as it reached the plane in which one of the pair of bearings of the universal support structure was mounted.

Analysis of Result

We concluded that the commercially available universal joint used in the suspension structure did not allow the pendulum equal flexibility in all radial directions and the pendulum could move with maximum ease only in the two mutually perpendicular axes of its two pairs of bearings.

It was also clear that although Charron ring was effective, its accurate centering with respect to the swing was crucial and this was very difficult to achieve without integrating the Charron ring with the suspension structure itself.

A series of experiments each trying to improve on the previously failed ones followed spanning over a frustratingly long period of time. It was about a year we had been into it, and yet success eluded us. But we would often take solace from R. Stuart Mackay who in his celebrated article in the American Journal of Physics, [21,180(1953)] wrote on the difficulty in designing and assembling of a Foucault pendulum, *"Finally it must be stated that the task of setting up a Foucault pendulum is a tedious one. One must achieve absolute symmetry if it is to turn at the correct rate, rather than seeking out a preferred direction. Besides the drive mechanism, special care must also be given to the clamping of the wire whose bending constitutes the pivot. Absolute perfection can be marred even by the crystal structure of the supporting steel wire."*

A Novel Idea & the New Design

We held intensive brainstorming sessions on how to fabricate an isotropic and uniformly rigid support, which while snugly holding the wire, would allow it to flex in all possible directions without being either slack or extra-tight along any one of them. Also the material of the support was to be such that it would withstand millions of abrasive contacts with the stainless steel wire rubbing against its surface twice in each cycle. Simultaneously, the wire also required protection from the abrasive contact with the lower end of its holder against which it lapped with great force twice in each cycle of swing.

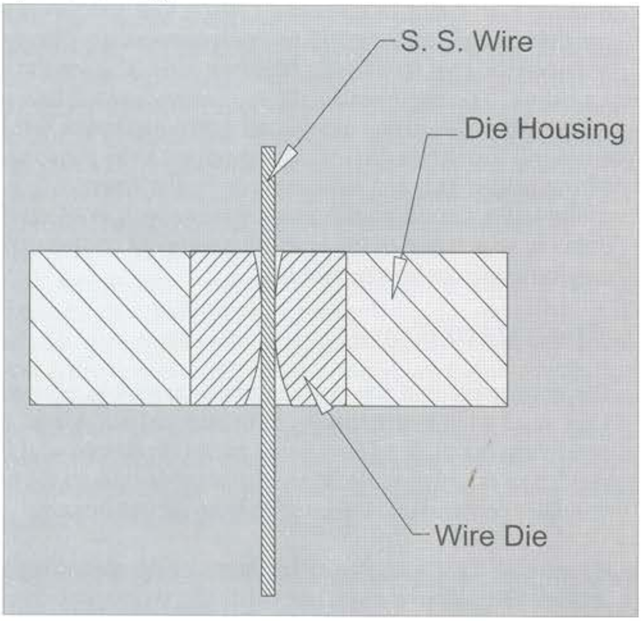


Fig. 7. Sectional view of a typical wire drawing die.

Mr. Mukherjee suggested that we might try a typical wire-drawing die which is used industrially to draw wires of the same gauge as the one we intended to use for our new set-up. The typical structure of a die (Fig. 7) with its smoothly flared end and the uniformly narrow neck was indeed an ideal possibility for holding the wire the way it was required for our purpose. Being made of tungsten-carbide alloy, the die was materially very tough and could easily withstand the forces of wear and tear. The smooth flaring at one side of the die could provide the safest contour against which the pendulum's wire would lap at the two extremities of its swing.

It took us some time to find out the source from where we could procure a Die that were meant for drawing a 16 swg wire, the size we decided to work with henceforth.

We eventually got hold of one that looked perfect and immediately got down to actually designing the new suspension system for our pendulum. The proposed new design was to be built based on:

* holding the wire by means of an actual wire-drawing die,

* the Charron ring was to become an integral part of the suspension system to avoid centering difficulties,

* inherent structural asymmetry of the wire (which normally is sold in coils) was to be taken care of.

After much thought and deliberations we came up with a new design of the pendulum (Fig. 8a & 8b).

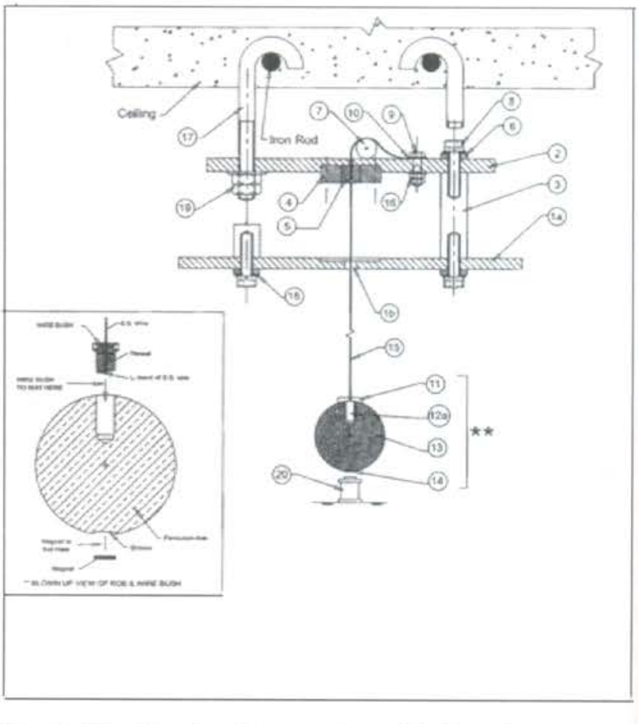


Fig. 8a. The New Pendulum – Assembly Drawing.

Part No.	Description
1a.	Charron Ring Plate
1b.	Charron Ring
2.	Mounting Plate
3.	Dowel Spacer
4.	Brass Housing
5.	Wire Die
6.	Cup Washer
7.	Aluminium Roller
8.	Allen Bolt
9.	Anchor Bolt
10.	Anchor Washer
11.	Fastener Bolt
12a.	Anvil
12b.	Blown up view of BOB
13.	Pendulum BOB
14.	Disc Magnet
15.	S. S. Wire
16.	Lock Unit
17.	Foundation Bolt
18.	Spring Washer
19.	M-12.7(TVS)Nut
20.	Driver Coil

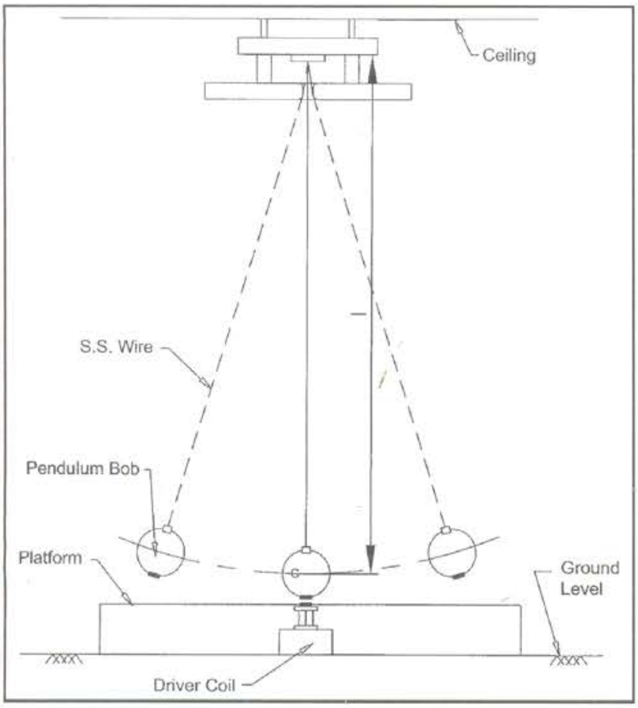


Fig. 8b. Schematic Diagram of the New Set-Up.

The New Suspension System

All the components of the new set-up were machined with great care in our workshop in order to ensure maximum possible dimensional accuracy of the fabricated parts. The suspension system comprised of two stainless steel plates of non-magnetic grade (IS 304) held exactly parallel to each other by means of three accurately machined dowel spacers 120° apart. The upper plate or the mounting plate (part no.2) of thickness 12 mm had a central undercut at its bottom surface for locating the brass housing (part no.4) for the wire die which was fitted exactly at the centre of the housing as shown in the diagram. The flared end of the die was kept on the bottom side to allow the pendulum wire wrap on its smooth surface at the two extremities of its swing. The brass housing in turn was secured to the bottom surface of the upper plate by means of three tap screws driven from the top of the mounting plate. The lower plate (or the Charron ring plate) (part no.1a) of thickness 16 mm had a central hole through which the wire was taken down. The diameter of this hole was to be such that the swinging wire of the pendulum, for the designed amplitude, would just touch the rim at the two extremities and thereby would prevent, due to frictional damping, any tendency to ellipse. In effect, the hole would then behave as the Charron ring (see Fig. 8b). The centre of this hole or the Charron ring (part no.1b) and that of the die had to be precisely in the same vertical line, so that in the still condition when the pendulum remained plumb under the weight of the bob, the wire passed exactly through the centre of the hole. This was ensured by turning the two plates together in the lathe and then centering them in the same setting of the machining operation with the holes for the dowel spacers already registered. The mounting plate was firmly held with the roof by means of three H.T foundation bolts (part no.17) again spaced 120° apart. The reason we chose to have three-point fastening for all parts of our new suspension unit was to make alignments easier. An aluminium roller with a narrow groove (part no.7) was used to slip the end of the wire over it before securing firmly with the help of the anchor bolt (part no. 9).

The Pendulum Bob

A six-inch diameter ball made of brass, which again was turned in the lathe in our workshop, served as the bob in the new set-up (part no.13). A threaded hole was made at the top of the bob, and a matching bolt with a central hole through which the lower end of the wire passed, was put inside it (part no.12b). In order to prevent the heavy bob, about 18 Kg in weight, from slipping off the wire under its own weight, the protruding end of the wire was bent at right angle after passing it through the hole in the fastener bolt. The bent portion being smaller than the bolt's diameter, driving the bolt down the threaded hole was no problem. A small piece of lead was put inside the hole against which the bent portion of the wire pressed as the fastener bolt was tightened and thereby prevented any possible slipping of the wire. At the bottom of the bob, exactly opposite to, and co-axial with, the centre of the fastener bolt, a thin groove was made in the bob for precisely locating a permanent ceramic disc magnet of diameter 25mm. The disc magnet was secured in place using superglue (part no.14).

We took extreme care in ensuring that no turbulence was set up in air when the bob moved to and fro; because if it did, vortices would form that might give rise to asymmetric perturbations affecting the pendulum's performance. To ensure this, the spherical surface of the bob was first finished to a high order of smoothness and then varnished. Moreover, the head of the fastener bolt (part no.11) was made round instead of being hexagonal so that the small irregularity in shape was not called upon air to play the role of the spoilsport. The round shape of the head of the bolt posed problem in tightening, which was overcome by providing suitable small holes in the rim and by making a special fastener tool for tightening.

The Driver Unit

The electromagnetic drive system we had been using for the earlier experiments basically remained the same except for the increased number of turns in the coil assembly of the new driver unit. The number of turns in the driver coil was to be increased keeping in view the heavier bob we used in the new design (Fig. 9a & 9b).

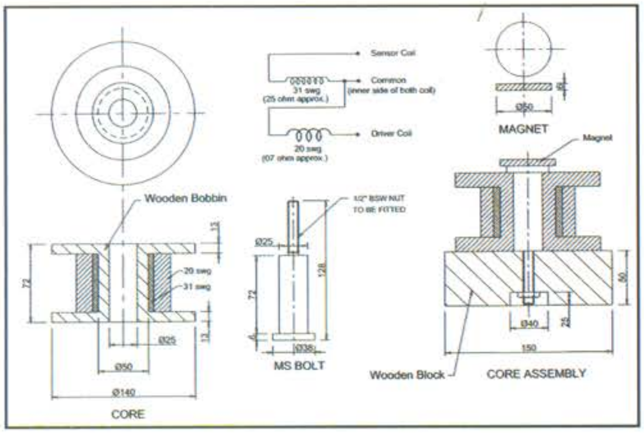


Fig. 9a. Diagram of the Driver Coil Assembly.

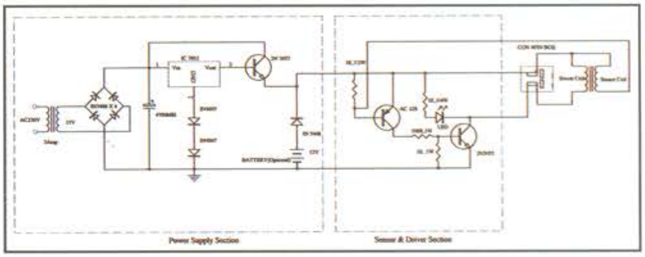


Fig. 9b. The control circuit.

The pendulum's drive system consisted of a permanent barium ferrite ceramic magnet glued to the bottom of the pendulum bob, a coil assembly (refer Fig. 9a) and a control circuit (refer Fig. 9b)). The coil assembly consisted of two concentric coils, the sensor coil and the driver coil, wound around a wooden bobbin through whose centre a soft iron rod passed. The inner coil or the sensor coil was made of 1080 turns of 31 swg super-enamelled copper wire and the outer coil or the driver coil had 1350 turns of 20 swg wire. Precautions were taken to avoid magnetic interference by the presence of ferrous material near the coil assembly.

The amplitude of swing became stable when the energy fed by the electromagnet to the pendulum system just compensated for the loss due to friction with air and at the support structure. The amplitude could be increased or decreased in our new system by decreasing or increasing the gap between the permanent magnet on the pendulum bob and the temporary electromagnet. A screw-jack mechanism (made of non-ferrous material) over which the coil assembly was kept, made this adjustment easy.

The Wire

A 16 swg stainless steel wire of the non-magnetic grade was used. Since such wires mostly come in coils, they develop a certain amount of structural bending. In order to remove the inherent bend in the wire, we had kept a length of the wire preloaded with 40kg weight for a minimum period of two months before putting it in the pendulum system.

Alignment of the system

As pointed out earlier, aligning a Foucault pendulum is a very delicate and tedious task. The centrality of the problem is to be able to achieve the following:

1) The wire, the axis of its grip (the wire-die in our system), the centre of the Charron ring, the c.g of the bob, the centre of the ceramic magnet and that of the electromagnet are to be aligned exactly along the vertical axis of the system.

2) An optimum value for the amplitude of swing is to be achieved such that the wire just touches the rim of the Charron ring rather than lapping over it and flexing beyond.

3) The portion of the wire that bends during each swing of the pendulum should, by all means, be held in perfect vertical position in the still condition. This means that the cross-section of the wire at the position of flexing should necessarily remain strictly horizontal when the pendulum is in still condition.

The beauty of our new design, as far as the question of alignment was concerned, was that it solved most of the problems by the innovative design features of the suspension system and by the very rigorous and accurate fabrication standard followed. Even before the installation, problems 1 & 3 above were mostly solved by making the suspension plate and the Charron ring plate parallel, and this was made possible by the integration of the Charron ring unit into the suspension unit- a unique feature by itself. This feature ensured that if one could successfully align the suspension plate exactly horizontal, then the centre of the Charron ring and the plumbed wire would fall exactly along the vertical through them should the wire-die be assumed to be housed perpendicular to the suspension plate by virtue of the precision in fabrication of the plate and the die housing.

Performance of the New Pendulum

The theoretical value of the pendulum's expected angular rotational rate at Kolkata (latitude 22°N) was calculated to be 5.8 degrees/hour using equation (9).

Observations were made and readings noted on hourly basis. A plot of angular displacement of the pendulum's plane against time was made for each day. The slope of the plot yielded the angular rate of rotation, which came out to be remarkably close to the theoretical value (Fig. 10). Our new pendulum missed the theoretical value by just 2 to 5 percent, whereas an error of up to 15 percent is considered acceptable world over. The performance was excellent by international standard.

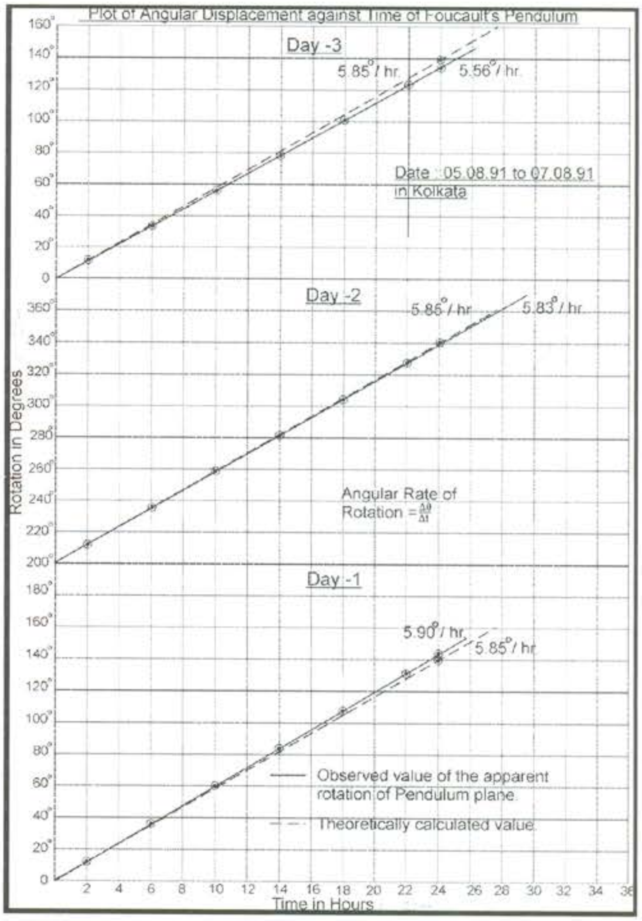
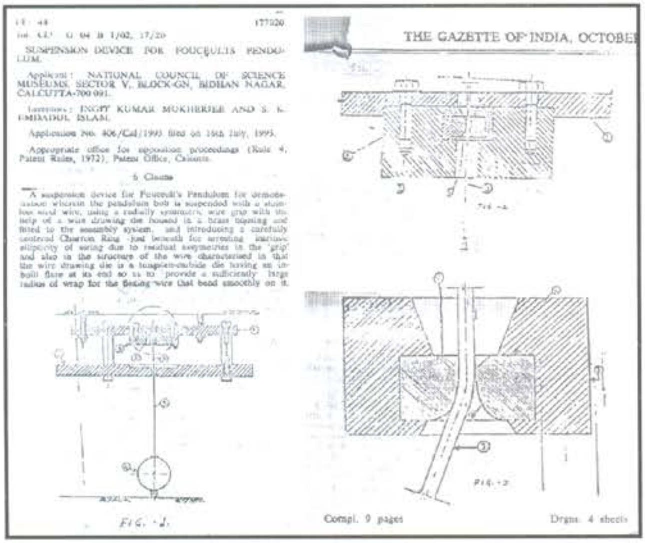


Fig. 10. Plot of Angular Displacement against Time.

Novelty of the New Design

The suspension unit of the pendulum had a few novel aspects: a wire-die as the new grip for the wire and integration of the Charron Ring with the pendulum's suspension unit.

These features of the new design were original contributions and hence merited a patent coverage. The patent had since been granted. A copy of the Gazette Notification in this regard is reproduced below (Fig. 11).



THE GAZETTE OF INDIA, OCTOBE

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Int. Cl.⁵ G 04 B 1/02, 17/20

SUSPENSION DEVICE FOR FOUCEULTS PENDULUM.

Applicant: NATIONAL COUNCIL OF SCIENCE MUSEUMS, SECTOR V, BLOCK-GN, BIDHAN NAGAR, CALCUTTA-700 091.

Inventors: INGIT KUMAR MUKHERJEE AND S. K. EMDADUL ISLAM.

Application No. 406/Cal/1993 filed on 16th July, 1993.

Appropriate office for opposition proceedings (Rule 4, Patent Rules, 1972), Patent Office, Calcutta.

5 Claims

A suspension device for Foucault's Pendulum for demonstration wherein the pendulum bob is suspended with a stainless steel wire, using a radially symmetric wire grip with the help of a wire drawing die housed in a brass bushing and fitted to the assembly system, and introducing a carefully centred Charron Ring just beneath for arresting intrinsic ellipticity of swing due to residual asymmetries in the 'grip' and also in the structure of the wire characterised in that the wire drawing die is a tungsten-carbide die having an in-built flare at its end so as to provide a sufficiently large radius of wrap for the flexing wire that bend smoothly on it.

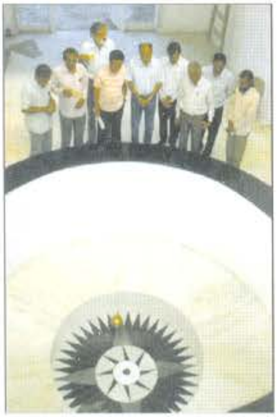
Compl. 9 pages

Drgs. 4 sheets

Fig. 11. Copy of Patent Gazette Notification.

Installation Sites

India's first successful Foucault pendulum for public display came into being in the year 1993 at IUCAA, Pune.



(Prof. Narlikar (5th from left) & his colleagues with the author and his colleague from NCSM watching the pendulum after installation).

Fig. 12. Foucault pendulum at IUCAA, Pune.

The success of the first installation brought a series of requests from many other scientific institutions and universities. The pendulum has since been installed in the following places besides Pune.

- Queensland Science Museum, Brisbane.
- Physical Research Laboratory, Ahmedabad.
- Regional Science Centre, Tirupati.
- DDU Gorakhpur University, Gorakhpur, U.P.
- Saha Institute of Nuclear Physics, Kolkata.
- TIFAC building, IIT, New Delhi.
- ONGC Golden Jubilee Museum, Dehradun.
- Istanbul, Turkey.

Our first two pendulum installations at IUCAA, Pune and Queensland Science Museum in Brisbane provided interesting contrast.

As was expected from theory, the pendulum at Pune (18°31'N) apparently turned 4.86° per hour clockwise, while in Brisbane (27°30'S) it turned 6.92° per hour anti-clockwise. The success of our new design was thus unmistakably established by experimental results from both the hemispheres.

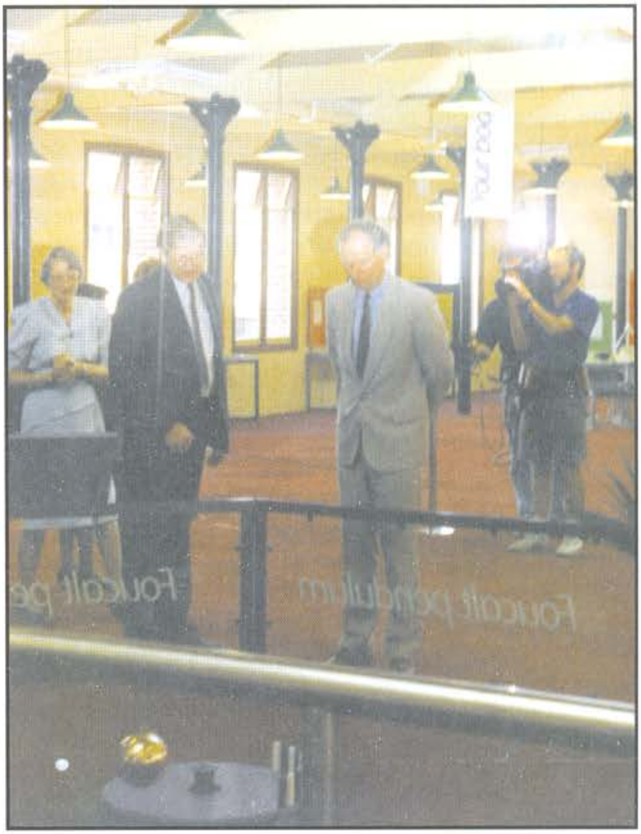


Fig. 13. Foucault Pendulum installed at Queensland Science Museum, Brisbane.

Select Readings:

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E Islam, is Director of Birla Industrial and Technological Museum, Kolkata.

Development and Mathematical Analysis of Double Gravity Well Exhibit

Indranil Sanyal *and* ***Nataraj Dasgupta***

Abstract

Double Gravity Well is a highly interesting exhibit, demonstrating the movement of a ball of mass 'm' simultaneously under the attractive forces of two centers of gravitation. When attempts to simulate the exact space-time curvature of such a force field by trial and error method failed, we resorted to a mathematical modeling using 3-D analytical geometry and plotted the exact surface. We then devised a practical method of fabrication calculating the cross sections of the surface at regular intervals. The solution of the equation of motion of the ball was worked out by solving the Euler-Lagrange Equation in elliptical coordinates. The solution shows unpredictable trajectories of the ball in the space-time curvature which is highly sensitive to initial conditions. We also extended the method in exploring fields with three or more gravity wells. The exhibit demonstrates some important phenomena in classical mechanics, classical electrodynamics, molecular physics and planetary physics and in some other fields.

Double Gravity Well exhibit demonstrates the movement of a ball (Planet) of mass m simultaneously under the attractive forces of two centers of gravitation (Suns). In physics, the problem is known as Euler-Jacobi problem or two-center Kepler problem. The mathematics involved in this particular exhibit is known as Euler's restricted three-body method which is used to solve for the motion of a particle under the gravitational field of two other point masses that are fixed in space. This problem is significant as an exactly solvable special case of the three-body problem, and an approximate solution for particles moving in the gravitational fields of prolate and oblate spheroids. This problem is named after Leonhard Euler, who discussed it in 1760. In this article, we apply Euler's method in designing a double gravity well as well as solving the equation of motion.

Modeling the exhibit

For a single gravity well exhibit, the force acting on a rolling ball is $F(r) = -\frac{\mu}{r^2}$. The gravitational potential $V(r)$ is proportional to $\frac{1}{r}$. When we plot $V(r) \sim r$ curve, where $r^2 = x^2 + y^2$, we get a rectangular hyperboloid, which is our familiar space-time curvature of a single gravity well (fig. 1). The trajectories of motion on such a surface can be easily calculated to be elliptical in nature from classical mechanics.

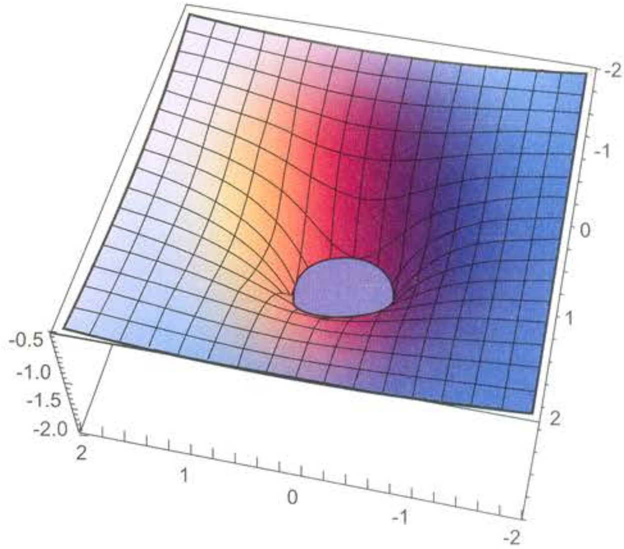

Fig. 1. A Single Gravity Well.

As the single gravity well modeling was successful, we applied the method of modeling to a double gravity well. It can be understood that the equation of the surface must have singularities at two points on the surface, say at x=± a, y=0. Thus we assume two centers of force acting on the ball to be fixed in space and let these centers be located along the x-axis at ±a. The ball is likewise assumed to be confined to a fixed plane containing the two centers of force. The potential energy of the ball in the field of these centers is given by

$$V(x,y) = -\frac{\mu_1}{\sqrt{(x-a)^2 + y^2}} - \frac{\mu_2}{\sqrt{(x+a)^2 + y^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where μ_1 *and* μ_2 are constants. We have assumed that the two gravitational fields are identical. Therefore, $\mu_1 = \mu_2 = \mu$ *(say)*. To plot this surface, we take $V(x,y)$ along negative z-axis, and we get

$$z(x,y) = -\frac{1}{\sqrt{(x-1)^2 + y^2}} - \frac{1}{\sqrt{(x+1)^2 + y^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

We have taken a=1 and for scaling, we have taken $\mu = 1$. The computer generated plot is a double gravity well (fig. 2).

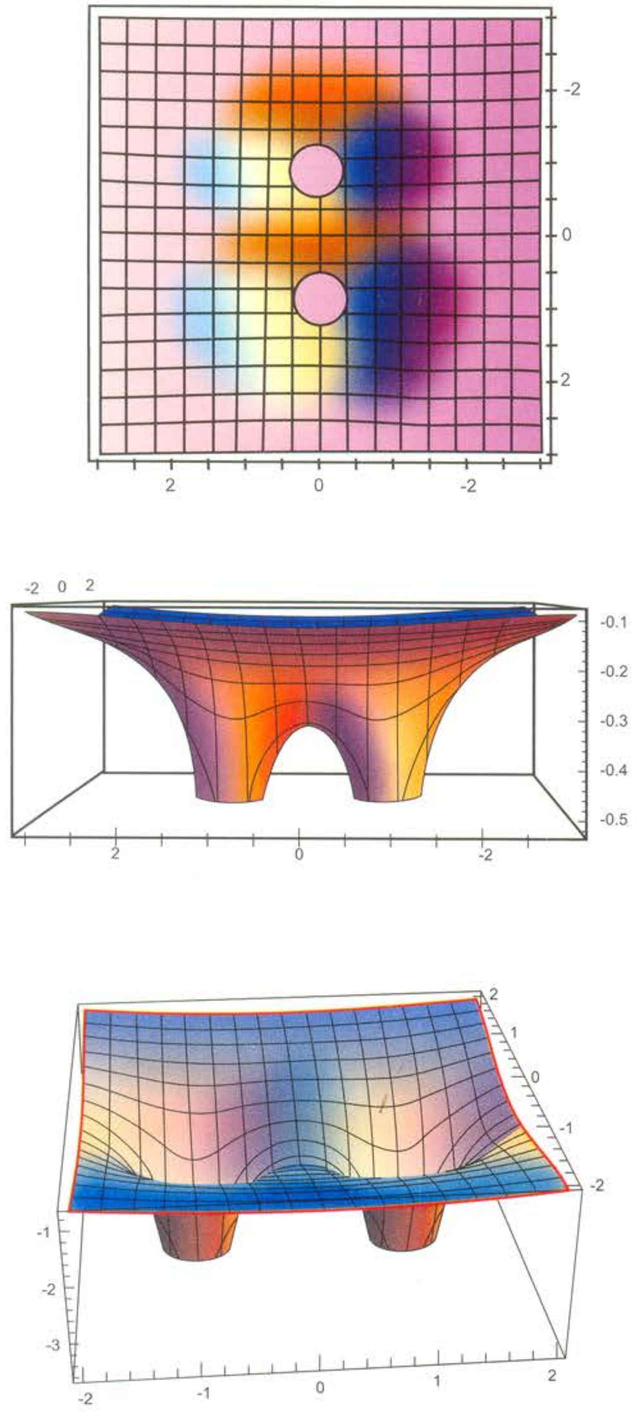

Fig. 2. Double Gravity Well (three different views).

However, if the strengths of the fields are different, the well takes an asymmetric form (fig. 3).

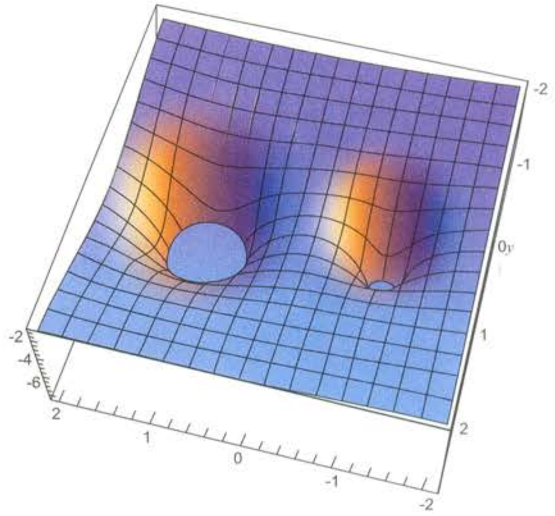

Fig. 3. Asymmetric Double Gravity Well.

The symmetric well has a cross section at its center as given below.

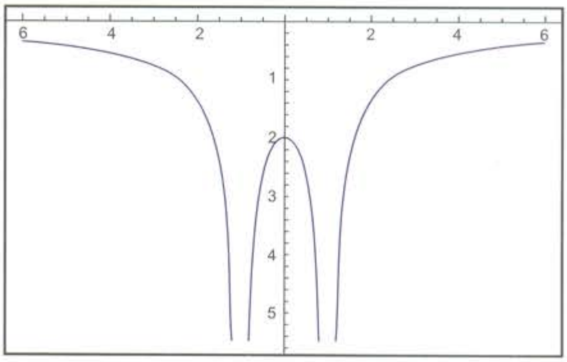

Fig. 4. Vertical Cross Section of a Double Gravity Well.

The above method can be used to design multiple well potential surfaces as shown below:

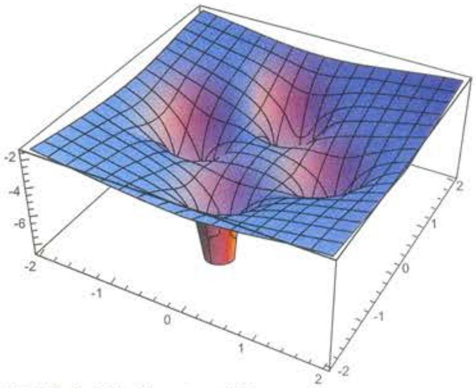

Fig. 5. Multiple Well potential.

Equation of motion and its solution

The problem of two fixed centers conserves energy. The total energy E is a constant of motion. In our problem (taking a symmetric double gravity well), the potential energy is given by

$$V(x,y) = -\frac{1}{\sqrt{(x-1)^2 + y^2}} - \frac{1}{\sqrt{(x+1)^2 + y^2}} \text{ ....} (3)$$

The kinetic energy can be simply written as

$$T = \frac{m}{2}(\dot{x}^2 + \dot{y}^2 + \dot{z}^2) \text{..................} (4)$$

where z is again related to x and y by the equation (2). So, there are practically two degrees of freedom for the rolling ball.

However, as the ball moves in a curved path, it has a rotational kinetic energy too. Taking this into account and taking mass and all other constants equal to one, the Lagrangian takes the form as given below (ω is the angular velocity of the ball, which is not a constant):

$$L = \left[\tfrac{1}{2}\left[\dot{x}^2 + \dot{y}^2 + \dot{z}^2\right]\right] + \frac{1}{\sqrt{(x-1)^2 + y^2}} + \frac{1}{\sqrt{(x+1)^2 + y^2}} + \tfrac{1}{2}\omega^2(x^2 + y^2)$$

$$\text{....................} (5)$$

Theoretically, the equation of motion can be solved by solving Lagrangian equation (6) for each generalized coordinate (q).

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} = 0 \text{ ....} (6)$$

We shall, however, solve the equations of motion by Euler's method in elliptic coordinate. The two centers of attraction can be considered as the foci of a set of ellipses. By treating Euler's problem as a Liouville dynamical system, the exact solution can be expressed in terms of elliptic integrals. Introducing elliptic coordinates,

$$x = a \cosh\zeta \cos \eta \text{ ....} (7a)$$

$$y = a \sinh\zeta \sin \eta \text{ ....} (7b)$$

and using the particular solutions for a Liouville dynamical system ($\mu_1 = \mu_2 = 1$), we get

$$u = \int \frac{d\xi}{\sqrt{E \cosh^2 \xi + 2 \cosh\xi - \gamma}} = \int \frac{d\eta}{\sqrt{-E \cosh^2 \eta + \gamma}} \text{ ....} (8)$$

Since these are elliptic integrals, the coordinates ξ and η can be expressed as elliptic functions of u.

The Orbits

The solutions give a series of orbits as shown below [Ref. Select bibliography No. 8]. The interesting point is the 8-shaped paths where the ball forms cross loops around the wells:

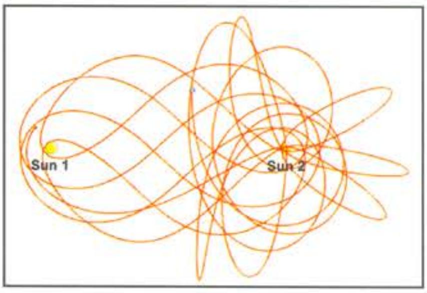

Fig. 6. Orbits around a double gravity well.

However, the practical orbits will be much different from this theoretical model because of three reasons:

1. Due to friction between the ball and the surface, the ball will continuously lose energy and move from an outer orbit to an inner orbit. In fact, the friction will act as a perturbation and we can see the precession of the orbit. The actual path will also depend upon the initial conditions.
2. Due to roughness of the ball and the surface at microscopic level, the ball may take any unpredictable turn near the central hump.
3. The effective potential of the moving ball is different from pure gravitational potential because the centrifugal force acting on the orbiting ball will contribute a potential of the value $m\omega^2(x^2 + y^2)/2$ which will oppose the gravitational potential.

For an asymmetric well, if the mass of Sun 1 is double that of Sun 2, then the ball will be drawn towards the bigger mass even if it is released near the smaller one (fig. 7).

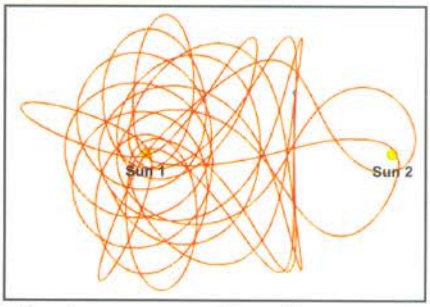

Fig. 7. Motion in an asymmetric well.

It has also been found that the motion is highly sensitive to initial condition and paths of two balls released from the same point diverge after some time (indicated with red and green lines):

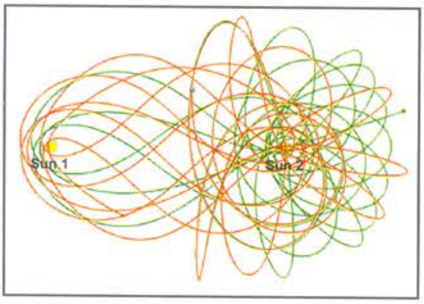

Fig. 8. Divergence of paths of two balls with same initial conditions.

One can easily see that if either center were absent, the ball would move on one of simple ellipses, as a solution to the Kepler's problem. Legendre and Bonnet have shown that according to the principle of superposition, the same ellipses are also the solutions for the Euler problem.

The ball's linear and angular momenta are not conserved in Euler's problem, since the two centers of force act like external forces upon the ball, which may yield a net force and torque on the ball. As a result, the ball will continuously change its path from an ideal superposition of two ellipses. However, the ball has a second conserved quantity that corresponds to the angular momentum or to the Laplace-Runge-Lenz vector as limiting cases.

The solution to the original Euler problem is an approximate solution for the motion of a particle in the gravitational field of a prolate spheroid. The corresponding approximate solution for a particle moving in the field of an oblate spheroid is obtained by making the positions of the two centers of force into imaginary numbers. The oblate spheroid solution is astronomically more important, since most planets, stars and galaxies are approximately oblate spheroids.

Fabrication

To start fabrication, we must revisit the equation (2)

$$z(x,y) = -\frac{1}{\sqrt{(x-1)^2 + y^2}} - \frac{1}{\sqrt{(x+1)^2 + y^2}}$$

Putting different values of z at a fixed interval, we got a series of contours in *xy* plane.

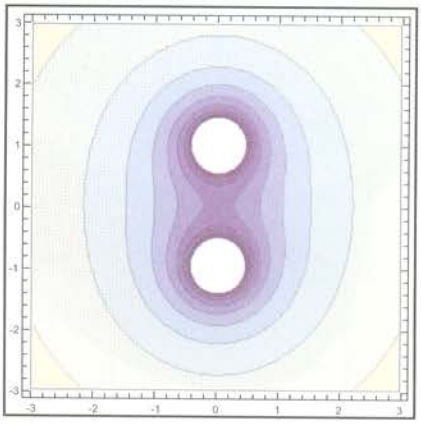

Fig. 9. Contour Plots.

These plots were used as templates to cut ply woods as shown below.

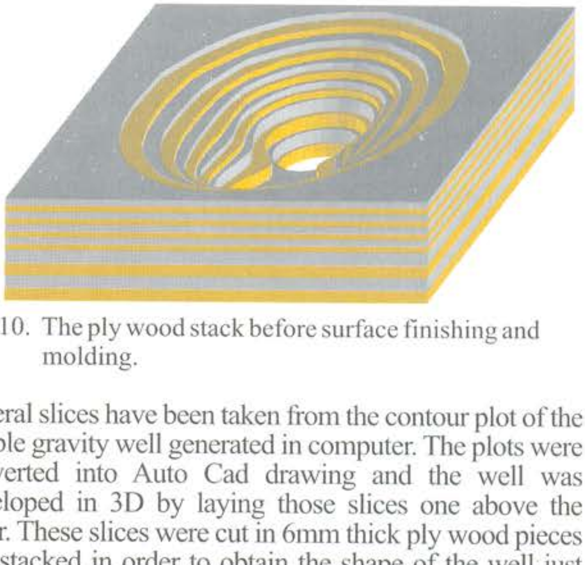

Fig. 10. The ply wood stack before surface finishing and molding.

Several slices have been taken from the contour plot of the double gravity well generated in computer. The plots were converted into Auto Cad drawing and the well was developed in 3D by laying those slices one above the other. These slices were cut in 6mm thick ply wood pieces and stacked in order to obtain the shape of the well just like generating topographical model of land forms. Since the contours are symmetrical, the foci were maintained by placing the contours at appropriate position with respect to four reference points (two on *x* axis and two on *y* axis).The contour of the well has been generated in discrete steps. The steps have been made smooth by applying epoxy resin putty in the groove to obtain a smooth surface. Once the shape of the well had been generated, it was checked by rolling a ball on it, which showed the motion similar to the simulation done by computer software. Then, a fiberglass mold has been taken. The final model of the well has been fabricated with fiberglass cast.

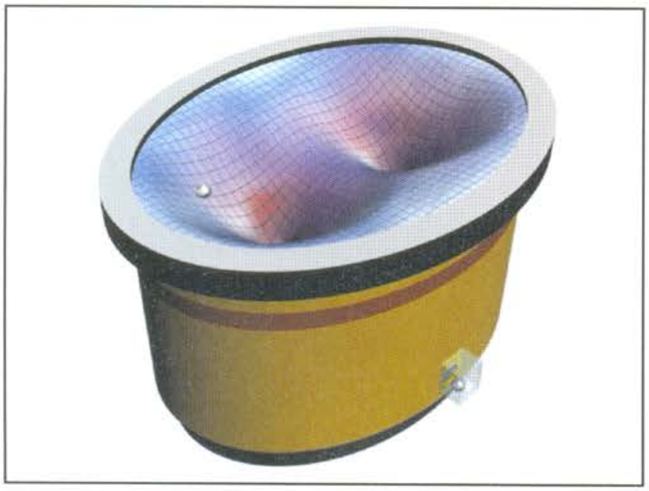

Fig. 11. The final exhibit (grid digitally superimposed).

Further works

The technique developed by us can be applied to generate and investigate upon multiple gravity wells as well as any arbitrary trial potential which may yield interesting result.

Acknowledgement

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Developing a Mechanical Television

Abdullah Mondal

Abstract

The invention by Paul Nipkow in 1884 consisting of a disk with holes spiraling into its centre shaped the development of television. John Logie Baird used Nipkow's disk to demonstrate the first Mechanical Television in 1926. The entire system was based on mechanical scanning of the objects and reproducing the images. Though mechanical television became outdated within fifteen years, it paved the way for development of modern television.

The working principle of a mechanical television is presented in an interactive exhibit 'Mechanical TV: How it Works' in the 'Television' gallery of Birla Industrial & Technological Museum. Keeping in mind the interactivity and operation of the exhibit by the visitors in a science museum setting, a simple and customized approach was adopted in developing the exhibit. The technique of scanning the object was thus done in a different way compared to that used in earlier Mechanical TVs. Here a parallel beam of light from a tailor-made object is first scanned by a Nipkow's disc. It is then collimated by a convex lens with large aperture. The beam is focused on a sensor, where it is picked up, amplified and fed to an electronic circuit. Instead of using a lamp as before a high glow LED is used for reproducing the image on a fluorescent screen.

Introduction

Development of television is considered to be one of the most striking achievements in the 20th century. We can not think of contemporary world without the existence of television. It's a window on the world that breaks down the barrier between nations and brings the world right into our living room. Few other media have had as much impact on us as television.

In 1926 John Logie Baird demonstrated the first television in London[1-3]. A series of inventions over a period of 50 years paved the way for its development. One such invention was done in 1884 by a German scientist, Paul Nipkow[1-5]. He invented a mechanical scanning disc, later came to be known as Nipkow's disc. The disc had perforations in the form of a spiral as shown in fig.1. When the disc rotates it scans the object in small strips, the number of strips is equal to the number of holes on the disc. At any moment a small portion of the object corresponding to the spot size of the light beam is scanned, and as the disc continues to rotate successive lines are traced out until the whole object is sequentially[5, 6] scanned. The scanning light beam bounces from the object and incidents on a photo cell where the signal is picked up for reproduction. Nipkow was unable to construct a satisfactory reproduction system because the signal was too weak to be converted back into light[1]. However, his contribution in designing the scanning disc had revolutionized the idea of mechanical television.

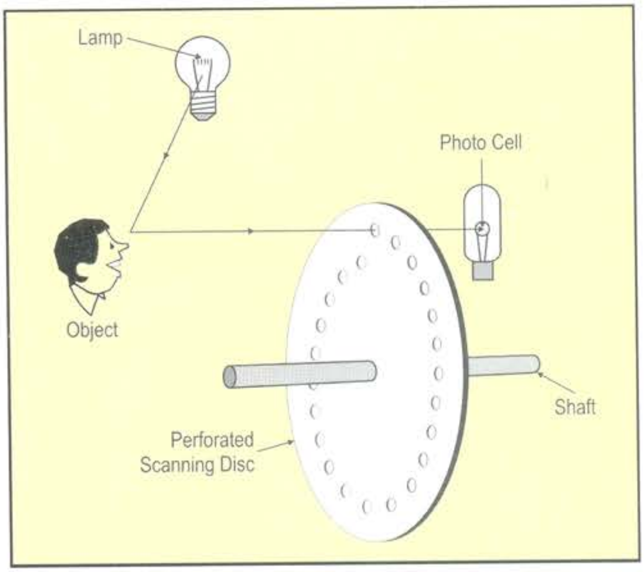

Fig. 1. The scanning Nipow's Disc.

In England, John Logie Baird devised a mechanical scanning system similar to Nipkow. However, he used valves to amplify the signal produced by a photoelectric cell. The signal lighted up a small neon lamp, in front of which a second scanning disc was set to rotate for reproduction. In 1926 Baird was able to transmit a silhouette[2] (fig.2.) and demonstrate his mechanical television.

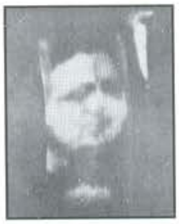

Fig. 2. Photograph of a human face produced by first Baird's Television in 1926.

Age of Mechanical Television

Following the success of Baird many people started working on television with renewed interest. Efforts were made in improving the mechanical scanning system and transmitting the image through air. Charles Jenkins in the United States founded Jenkins Television Corporation[3] in 1928. In the same year, using mechanical scanning system, the first regular experimental television broadcast[3] were made by the station WGY in New York. Soon British Broadcasting System (B.B.C.) adopted Baird's system as the foundation for a series of experimental broadcasts[3, 7]. Demonstration of such a television setup in operation is shown in the fig. 3.

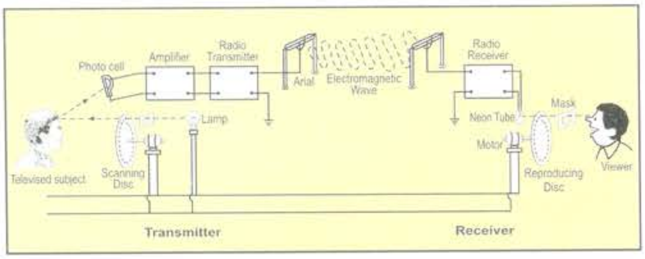

Fig. 3. Baird's Mechanical Television System.

Though image quality of 30-line transmissions steadily improved with technical advances[8, 9], image resolution remained relatively low, ranging from about 30 to 120 lines or so. This is because only a limited number of holes could be made in the rotating disks, and disks beyond a certain diameter became impractical. In 1931 Radio Corporation of America (R.C.A.) introduced a receiver[3] with kinescope tube developed by Zworkin. By 1935 R.C.A. developed a completely electronic television system. The world's first regular broadcasts of television programmes were begun by B.B.C. in London in 1936 using both mechanical and electronic scanning systems[1]. Instead of a Nipkow disk, several other technologies were also used in mechanical television. Other arrangements often made use of a rotating drum with holes or a series of mirrors fitted on it. However, images produced by mechanical scanning systems still remained unsatisfactory. The last mechanical television broadcasts ended in 1939. Mechanical systems were in use from 1928 to 1939, overlapping the all-electronic era by three years[7].

Design Challenges

Science museums and centres are the places of learning through exhibits and educational activities. In Birla Industrial & Technological Museum, most of the exhibits are participatory in nature. In such an exploration centre, visitors themselves operate the exhibits by pressing the buttons, rotating the handles or participating in other ways. For demonstration of the working principle of a mechanical television in such a setting, particularly its demonstration in the 'Television' gallery, an inventive approach was needed in designing the exhibit. First of all the entire system of the mechanical television - especially the scanning and reproduction discs - should be kept in an illuminated or semi-illuminated area in contrary to Baird's mechanical scanning to facilitate the visitors to see and correlate the scanning and reproduction processes. In such a situation light detecting sensor produces continuous signal in addition to the signals produced by the Nipkow's disc and forms a background optical noise. To overcome the difficulties it was necessary to design a suitable scanning system and that was achieved by modifying the conventional method of scanning the object. The object was tailor-made and instead of reflected light, light passing through the object is allowed to scanning. Prior to reaching the sensor it is collimated by a convex lens so that a single light sensor could pick up the signals. This makes the exhibit not only simple in fabrication but also reduces the use of multiple sensors. Secondly, as the exhibit is to be operated by the visitors themselves, the operation was also made simple. Two options were given to interact with the exhibit, one being switching on the exhibit by pressing a push button switch, and the other one is controlling the light that is incident on the object. When incident light is totally blocked casting of image on the screen disappears. For comparison and to portray the classic experiment a model of Baird's Mechanical TV is put beside this exhibit.

Development of the Exhibit

The most important part of the exhibit is a pair of identical Nipkow's disc, one for scanning the object and the other for reproducing the image. We used 6 mm thick aluminium plate for making the discs. The disc diameter is 45 cm and 14 drill holes were made on it in the form of a spiral. The diameter of each hole was maintained at 9 mm. While experimentation, diameter of the holes was varied up to 15 mm but it resulted in lesser number of holes on the disc. Due to practical constraints in the experimental set up, the disc diameter could not be increased further. It means the object is now scanned with lesser number of lines and enhanced illumination, but at the same time it leads to poor image resolution. On the other hand, experimentation was carried out with 6 mm hole size and with increased number of holes, but better results were found at an optimum size of about 9 mm.

Choice of object was interesting in the process of this exhibit development. As discussed earlier, light should pass through the object before reaching the scanning disc. A letter 'H' was cut on a metal sheet, the outline of which formed the desired object. Parallel light from a source is allowed to pass through 'H' as shown in the schematic diagram (fig. 4.).

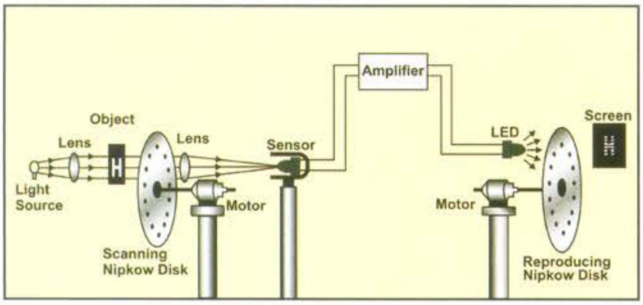

Fig. 4. Schematic diagram of the Mechanical TV developed at BITM.

It is scanned by the scanning Nipkow's disc and passed through a convex lens with aperture 15 cm and focal length 30 cm. The lens converges the scanning beams and a light sensing diode picks them up as signals. The signals are amplified by electronic means and fed to a high glow light emitting diode (LED) placed in front of the reproducing disc. The intensity of LED varies as per the strength of signals it receives from the sensor. Both the discs rotate in unison. While fixing the discs on the shaft care should be taken to avoid any phase lag between the discs. In short, there should be one to one correspondence in respect of positions of the holes in the two discs. A fluorescent screen is placed behind the reproducing disc. When the exhibit is operated image of the letter 'H' is produced on the screen as shown in fig. 5.

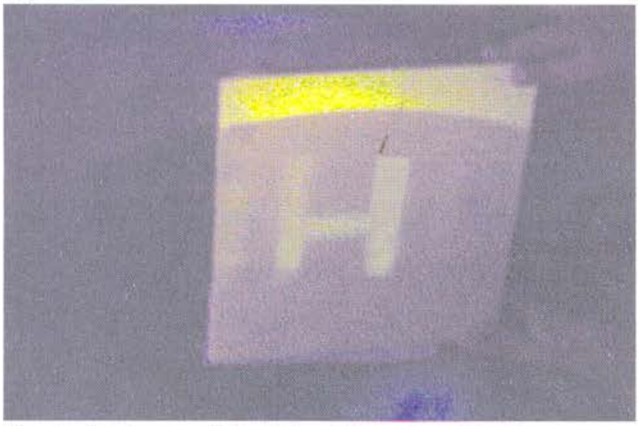

Fig. 5. The image of the letter 'H' produced by the Mechanical TV at BITM.

During experimental phase both the wheels were mounted on a single shaft. But for the television gallery, considering its ambience and display, separate shafts were used (fig. 6.) in making the final exhibit. To avoid any phase lag they were coupled through chain-sprocket system. The drive was given from a single DC motor and the discs are made to rotate at 400 r.p.m. To facilitate obstructing the incident light on the object a shutter was provided. Visitors can rotate a handle to block partially or fully the incident light. When a portion of the object is illuminated image on the screen is created accordingly. This helps the visitors apply their thought process to comprehend the working principle of a mechanical television, a television that paved the way in making a window on the contemporary world.

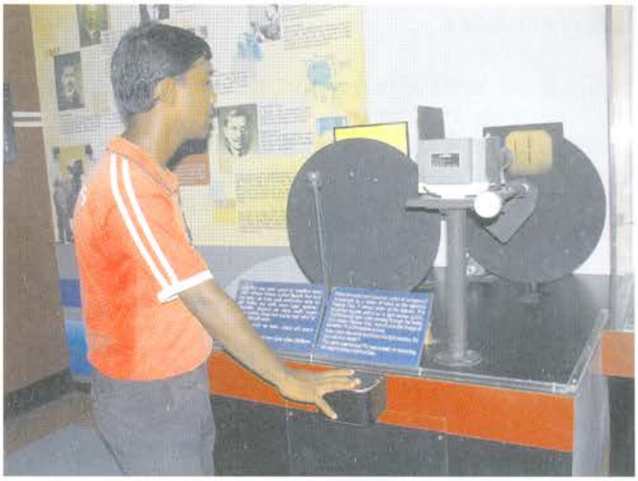

Fig. 6. A visitor is exploring the Mechanical TV in the Television Gallery.

Conclusion

Some of the inventions that greatly influenced the society and brought a dramatic change in enhancing the quality of life, television is one of them. It is necessary to portray its genesis; the mechanical television to the people. For demonstrating its working principle in a science museum an interactive exhibit can be made with some modification, particularly in the scanning system. The disc diameter can be made even larger with incorporation of more scanning lines, but keeping the hole diameter optimum. However, from maintenance point of view it is better to use a single shaft for both the discs.

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